Report on Conceptual Systems Analysis of Drilling Systems for 200-m-Depth Penetration and Sampling of the Martian Subsurface

James D. Blacic, Donald S. Dreesen and Theodore Mockler

GeoEngineering Group
Los Alamos National Laboratory

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Executive Summary

A conceptual systems analysis study was performed to identify critical issues and assess the best technologies for accessing and sampling the Martian subsurface to a depth of 200 m. A near-equatorial landing site is assumed at which the average surface temperature is 200 K and the atmospheric pressure is 600 Pa. The shallow rock to be penetrated is assumed to be an interbedded sequence of basaltic volcanic rocks, fine-to coarse-grained sediments and conglomerates, impact glasses and breccias, and ice in the form of pore cement, pure ice lenses or massive ground ice. A landed mass of 750 kg is assumed, of which, 250 kg is allowable for the drilling/sampling system. Power of 1000 Watt-hours per Sol is assumed available for drilling operations. The target depth must be reached and all sampling completed 200 days after landing.

An extensive search of sources identified a LONG LIST of 36 distinct systems that might be capable of achieving the mission objectives and for which there was some description and/or data under terrestrial conditions. This list was reduced to a SHORT LIST of 15 systems on the basis of first order decisions of whether or not each system could meet fundamental mission constraints. This remaining list of systems was subjected to more detailed engineering analysis to identify those best able to meet mission requirements and constraints. This screening eliminated all existing terrestrial systems, but a list of critical subsystems was determined from which custom prototype systems could be constructed for testing. The main problem in identifying specific systems was the general lack of quantitative operational data to use in calculations and to form objective criteria for comparison and selection. At temperature and pressure conditions close to those assumed for the Martian environment, no data was found for any drilling process. As a result, only general conclusions could be reached, the primary of which was that ***only high-efficiency, mechanical, overburden-type drilling approaches are feasible for this mission*** with hole diameters of ~35 mm and core samples of ~15-mm diameter which may have to be sub-sampled to meet contamination constraints. Mobilization and transport of drill cuttings in the shallow drilling environment was identified as a major technical challenge that may require breakthrough technology development.

To illustrate what a credible system might look like for this mission, three EXAMPLE SYSTEMS were constructed from the analysis combining the best subsystems for rock comminution, drill-hole conveyance of subassemblies, drill-cuttings transport and disposal, well bore stabilization, power transmission from surface to hole bottom, and thermal management. Familiar cuttings transport methods are inefficient and possibly ineffective at shallow, near-vacuum wellbore pressure. Therefore, continuous coring was found to be feasible and probably the most efficient method to remove material from the bore, and so all samples were assumed to be of this form. The example systems are described conceptually and total system estimates for mass and power are given. We conclude that the assumed mass and power mission constraints are feasible.

The analysis concludes with recommendations for subsystem research and prototype demonstrations that must be performed before any detailed mission design can be undertaken.
Our priority list of recommendations are:

1) **Investigate critical subsystems that require early and extensive laboratory-scale testing.** These include comminution, cuttings transport, drilling process automation and robotics, and sample handling.

2) **Conduct extensive testing in a 600 Pa, 200 degree K, and CO_2-filled chamber**.

   a) Perform mechanical drilling demonstrations:

- Rotary, percussive, and combined methods at various percussive frequencies, rotary speeds and thrust levels.
- Large variety of rocks and formations.
- Collect extensive data to model bit performance and optimize cutting performance over a wide variety of operating conditions.

  b) Investigate bit cleaning and cuttings transport.
  c) Investigate bit cooling and core heat-up.
  d) Perform rock strength and coefficient of friction measurements for sample drill system materials and special, extra-dehydrated rock samples (Martian simulants).

3) **Perform demonstrations of example systems in the laboratory and in the field.**

   a) Develop a test bed for developing sensors, telemetry and control systems.
   b) Demonstrate remote-controlled and automatic-controlled drilling in Mars-like drilling environments with various drilling systems.
   c) Use appropriate time-delayed communication for remote control.
   d) Test various control methodologies under realistic simulations of Martian conditions.
   e) Develop test bed for evaluating and determining the best technical approach for bore-wall stabilization.

4) **Investigate total system thermal management.**

5) **Investigate methods for prevention of contamination of core and samples.**

6) **Determine the learning curve for developing test plans and procedures for testing second generation, optimized systems based on results from laboratory investigations and field demonstrations**.

Introduction and Background

Recent robotic orbital and lander missions at Mars are part of a renewed campaign of exploration that seeks to build on the early successes of the Viking program. Current plans feature a vigorous series of orbital, surface and subsurface robotic missions with a probable return of a small number of atmosphere, rock and soil samples to Earth, and culminate in human exploration before the end of the second decade of the new millennium. The latest discoveries of this program are lending increasing support to models of a water-rich Martian history in which most of the remaining water is now thought to reside in the subsurface (e.g., [1]). Furthermore, the top-level goal of seeking evidence of extant or fossil life on Mars has evolved a strategy of "follow the water," since experience shows that life on Earth seems to require the presence of liquid water. These developments have led to a compelling argument for deep subsurface in situ measurements and sampling on Mars, a challenge never faced by planetary science on any body other than the Earth.

Mars interior in situ measurements or sampling implies an access technology. For very shallow depths, scraping, scooping, digging, quasistatic or kinetic mechanical piercing, augering or even explosive excavation techniques can be considered. However, for depths below a few meters and certainly below a few tens of meters, some kind of small-bore drilling technology is needed. Numerous and highly varied drilling technologies have evolved to produce bores from several meters up to12-km depth [2, 3] in a wide range of terrestrial conditions. Resource exploration and exploitation has sponsored the development of most drilling technology, and

scientific drilling has modified existing drilling technology to support the ocean drilling program and a much smaller continental scientific drilling program. While varied in their details, all drilling methods involve the application of energy to destroy the aggregation and mechanical strength of rock constituents and remove them to produce a void. For terrestrial drilling, the fundamental selection factor driving technological development has been cost and secondary factors that are strongly related to cost, for example, advance rate and flexibility. In extraterrestrial scientific drilling, cost is also a fundamental driver but the secondary factors are much different. Engineering R&D, fabrication cost, operating cost, safety, all cost-related factors that have strongly determined terrestrial drilling machinery designs, are relatively small in comparison to transportation costs for a deep drilling system on Mars. Hence, we believe that mass will be the most important factor determining design of extraterrestrial drilling equipment. Many secondary factors such as power and down-hole cooling are directly related to mass. However, there are some subtleties here. It does little good to land a low-mass, low-power drilling system on Mars if the drill proves incapable of penetrating the rock encountered in the subsurface, whose characteristics are almost totally unknown beforehand. Thus, high degrees of flexibility and reliability will also be strong factors in drilling systems design. Deep drilling in previously unexplored areas in complex geologic and hydrologic environments tends to be a trial and error process. Partial plug back, sidetrack and re-drill, or re-drill from the surface of a near-parallel bore using modified equipment and/or procedures, are frequently done to avoid expensive repositioning of an immovable drilling assembly or to eliminate or control some other unforeseen difficulty. Total loss of a relatively deep hole and re-drill from the surface is common in the more difficult drilling environments. Deep-well drilling programs include numerous contingency plans and rely heavily on the ability to bring in modified drilling and well completion equipment in a timely manner. Because of the transportation factor, this terrestrial approach to drilling will be difficult to duplicate on Mars.

System design is further complicated by the fact that access alone will likely be insufficient to meet many of the scientific goals of subsurface investigations. For example, the astrobiology goal of searching for fossil or extant life in putative Martian subsurface ground water will almost certainly require acquisition of samples conveyed to surface instruments for analysis and/or return to Earth. Subsurface sampling in the context of planetary protection is a daunting technological challenge in itself that will have to be integrated with the drilling technology. All of this is still further complicated by the need for a high degree of automation required for robotic investigations that reduce mission costs and reduce the risk to human explorers.

Hence, the strategy that is evolving for Mars subsurface exploration features a phased approach in which successively deeper, robotic penetrations and more sophisticated in situ measurements and samplings will be attempted, with an ultimate target depth of several kilometers. This strategy is based on analyses from several workshops held over the last two years. In these discussions, experts in planetary science, astrobiology, spacecraft engineering and terrestrial drilling from government, universities and industry met to conceptualize plans for technology development and missions to achieve the deep sampling goals within the broader context of Mars exploration. An example mission plan shown in Figure 1 highlights the need for a deep drilling and sampling technology development (Tasks 14-24) that must begin immediately if this aggressive mission schedule is to be achieved. In this phased approach, the first significant penetration of the subsurface is envisioned as a robotic shallow subsurface sampling

mission in which "shallow" is defined as ~200-m depth. While penetration and sampling to this

Figure 1. Example mission and technology development plan for Mars subsurface sampling.

Earth would be a relatively trivial task in most typical commercial drilling contexts, the same objective under the conditions and constraints of a low-mass and low-power autonomous mission to Mars represents a significant challenge.

Objectives

Logically, the first steps of any plan like that shown in Figure 1 would include an evaluation of available technology and a preliminary systems engineering study to identify key elements for development (e.g., Task 43 of Figure 1). As part of the Surface Systems Thrust Area of NASA's Technology Development Program, we have been tasked to perform a conceptual systems analysis of the shallow, 200-m-depth sampling mission. This document reports the results of the study.

The study statement of work defines the following objectives of the analysis:

- State the mission definition which includes the mission requirements, resources, and constraints for a 200-m-deep subsurface sampling system.
- Identify the most significant impacts the mission definition will have on the Martian sampling system as compared to a similar system to produce the same results on Earth.
- Make an initial attempt to identify and evaluate the best technology to achieve the objectives for the 200-m-depth mission.
- Propose two or three systems for early development and Earth-based evaluation.
- Produce conceptual designs for the final two or three systems, and analyze and evaluate the designs.

Mars Surface Environment Assumptions, Mission Constraints and Implications for Drilling

There has been no formal mission definition for any of the envisioned subsurface investigations we have discussed above, and so the Mars environment and mission constraints are not well determined at this time. Nevertheless, previous workshops and planning exercises have discussed these issues to the point where, <u>for the purposes of this study</u>, we defined the Mars surface and subsurface environment in which the shallow drilling/sampling system would operate. We also specified what we believe to be a reasonable set of mission constraints for mass, power and duration. In the next few sections, we present the environment and mission constraint assumptions that we used in the study and their implications for the drilling systems to be evaluated. The NASA sponsor agreed to these mission specifications and study assumptions early in the process. While certain to change as new data on Mars are obtained and mission planning progresses, these assumptions allow us to quantify our analyses and achieve the initial systems screening that is needed at this time. The results of the analysis can also identify assumed mission constraints that may have to be relaxed to reduce risk of mission failure.

Spacecraft Configuration and Siting

We will assume that the spacecraft carrying the drilling system will have a circular platform for equipment that is 2.5-m in diameter with an outer exclusion zone of an ~0.25-m annulus for landing rockets, tankage and related equipment. We assume that a cylindrical

equipment bay will have a deployed height of ~4 m, and stand off the surface a distance of 1 m, supported by three legs that will have leveling capability of up to 30 degrees. We do not discuss the details of surface deployment, but conceptually assume that there will be a need to erect some form of vertical derrick and deploy solar panels and possibly radiators. We also assume the spacecraft structure, after leveling is completed, will provide a structural working floor of approximately 2-m diameter. We assume the platform is 1 m above the surface and is sufficiently robust to allow assembly and operation of the drilling system. The total mass of the landed craft will be assumed to be 750 kg of which 250 kg will be allowed for the drilling/sampling system exclusive of power and other utilities.

We assume that drilling will be initiated from the landed craft and no movement beyond the working floor space described above will be required to initiate the 200-m-deep hole. We assume that the drilling and sampling machine (surface system as opposed to bottom-hole and drill-stem components) will be able to remain inside of the transport vehicle if the design is dimensionally compatible. The drilling and sampling system may rely on the transport structure for dust, radiation, and temperature shielding to the extent that the transport requirements provide those features.

We assume that the landing site will be at low, equatorial latitude (+/- 25 degrees) in a relatively low-lying area of low to moderate small-scale relief, and that the average surface temperature is 200 K.

Atmosphere

Composition

Gases: From the point of view of drilling, we will assume that Martian air, or the 95.3% CO_2 component of the air, is the only useful gas that will be available in situ. We further assume that it will not be possible to collect the small amount of water vapor present in the Martian atmosphere or other trace gases.

Dust: We assume that seasonal dust storms have the capacity to cover horizontal surfaces with rock dust layers, composed of particles up to about 100 μm diameter, and up to a few tenths of millimeter depth.

Pressure

We will assume that the average surface barometric pressure and its variation will be 6 +/- 2 mbars (600 +/- 200 Pa). Liquid water and ice are assumed to be unstable on the surface at the drilling site.

Wind Loading

We will assume that the average and maximum wind velocities will be 5 m/s and 50 m/s, respectively. Assuming worst case temperature, wind velocity, and barometric pressure, the maximum wind loading on the landed spacecraft is anticipated to be approximately 90 Pa (9 kgf/m^2). We assume that the space craft and drilling system will have a low enough center of mass that the maximum wind loading will not tip the vehicle, and that leveling will make the craft and system more stable. Based on these assumptions, any requirement to anchor the drilling system (and spacecraft) to the Martian surface will be to provide the required drilling thrust (weight on bit = WOB), and not to preclude the effects of wind loading.

Slope and Terrain

The effects of landing surface characteristics will be to limit the ability of the spacecraft to successfully anchor to the surface and deploy the drilling system. We do not consider hazard avoidance in landing or any surface mobility.

Roughness

We will assume that there is a high probability of the lander encountering rock boulders up to ~0.5-m diameter, the assumed affect of which will be to produce up to a maximum inclination of the equipment platform and no other adverse effects. We assume that if one or more of the landing leg pads lands on potentially unstable boulders, the leveling process will shift the pads to more stable surfaces (without toppling the craft) until a highly stable footing is achieved before the final leveling is undertaken.

Slope

We will assume that the combination of local terrain slopes and roughness will result in a maximum inclination of the equipment platform of 30 degrees to the horizontal upon landing which will subsequently be leveled-out. We also assume that the system will be able to relevel and reposition the drill string to a very limited degree to adjust to any settling or shifting of the drilling platform after drilling has begun but not completed.

Strength

We assume that the strength of the surface material at the landing site could vary from almost zero (loose, unconsolidated sand) to very high values (solid, unweathered basalt, or igneous rock). The affect of the surface rock strength will be expressed in the design of any anchoring system that may be required and in the start-up of the sampling borehole. We did not analyze anchoring systems in any detail, but point out the potential need for this subsystem. Anchoring the spacecraft to the surface may be necessary if drilling systems require reaction to a vertical thrust in excess of 2085 N (75% of 285 kgf, weight of the leveled spacecraft) or if worst case surface slope/strength/wind load conditions require anchoring for platform stability.

Composition (Corrosivity)

Dust and surficial materials are assumed to be weathered basalt chemistry, possibly altered by the ultraviolet solar flux to produce highly oxidized, possibly corrosive particulates. The practical consequences of this are that 1) organic engineering materials (hydrocarbon polymers, elastomers) are assumed to be unstable and to be avoided wherever possible, and 2) the drilling system should operate within a weather-tight environment to protect all mechanical mechanisms from erosion and corrosion due to dust.

Lubricity

The extremely low moisture content of the atmosphere, and presumably the Martian surface may produce higher coefficients of friction between drill system components and the bore wall, in joints and fractures in the surface rocks, and between drill cuttings and broken core surfaces. This results in a potential problem of specifying lubricants that are compatible with bio-isolation (non-organic).

Insolation/Radiation

Ultraviolet and ionizing radiation at the Martian surface are assumed to render organic engineering materials unusable. Ionizing radiation may also adversely affect electronic instruments and control systems, but we do not consider that in this study.

Mission Constraints and Assumptions

Mission Objectives

Since there is no officially accepted Mars drilling mission at this time, it was necessary to generate some straw man mission objectives that could be agreed upon for the purposes of this preliminary analysis. While somewhat arbitrary, some set of objectives and resulting mission constraints had to be made to serve as a basis for even the simplest calculations and comparisons. The essential objectives, constraints, assumptions and implications for drilling/sampling systems are discussed in this and following sections.

Produce a near-vertical, 200-m-deep sampling and monitoring hole in the Martian subsurface

In order to obtain samples and perform in situ science measurements at target depth and above, it will be necessary to penetrate and stabilize all likely rock types that may be encountered. While we don't know the full range of possibilities, best estimates from the survey by Clifford [1] and workshop discussions result in a minimal list of rock materials as follows:

1) **Basalt:** Solid, fractured, vesicular, and/or weathered.

2) **Sediments:** Consolidated and cemented, unconsolidated, fine-grained lake bed deposits, evaporites, fluvial sands to conglomerates, and/or very poorly sorted glacial deposits.
3) **Ground ice:** This material may not be stable, depending on latitude of drilling site and near-surface porosity structure, but is assumed present for the purpose of drilling technology assessment; ice could be present in the form of pore cement, pure ice lenses or massive deposits.
4) **Crater debris:** By analogy with lunar samples, these could consist of melt sheet glasses and/or poorly-sorted breccias, partially to completely welded together.

In addition to penetrating all rock types encountered, we assume that it will be necessary to discern, monitor, and document any penetration of high-pressure fluids and/or unstable CO_2 or methane clathrates that may be encountered above 200-m depth. While it is less likely they will be encountered at shallow depth than at several kilometers, we cannot predict the depth of sealing from the atmosphere and hence the geometric distribution of stable H_2O-CO_2-CH_4 phases in the subsurface with any certainty. Therefore, any robust drilling system must be prepared to deal with a wide range of eventualities. However, to simplify the analysis at this early stage, we assume that the drill system will not be designed to assure the capacity to continue drilling if pressurized formations are encountered. Instead, we require only that the drill sensing system monitor and sample flow from the pressurized zone, and that the surface support package monitor and sample subsurface flow.

Conduct geophysical logging

Drilling process and science measurements must be made while the borehole is being drilled ("measure while drilling," MWD), between bit runs and immediately after drilling is completed (logging), and subsequently instrumented for long-term measurements (final well

completion). The details of science and operations measurements are not well defined at this time, but we list those that we believe will be likely candidates. Potential downhole measurements to be made during and after drilling and in the completed bore to support science and engineering objectives are:

1) **MWD**
   a) Bottom-hole temperature
   b) Circulating and bottom-hole pressure
   c) Borehole caliper (just below the overburden casing or bore stabilizing system)
   d) Natural gamma ray or other chemical/mineralogical measurements
   e) Drilling process – e.g., WOB, bit torque, bit rotation speed, bottom hole assembly (BHA) and core temperatures and other measurements associated with specific drilling approaches

2) **Science During Operations**
   a) Volatile gas sampler
   b) Reduced carbon detection or other biologic materials detection
   c) Acoustic monitoring using surface sensors

3) **Science Post-Operations.**
   a) Instrument borehole for long-term monitoring and logging:
      i. Undisturbed (recovered), post-drilling temperature log
      ii. Borehole rock chemical composition and mineralogy/petrology log
      iii. Resistivity log
      iv. Acoustic velocity log
      v. Televiewer log
      vi. Borehole seismic array

Expose and acquire samples

We assume that a primary mission objective is to acquire subsurface rock and soil samples of at least 1000-mm^3 volume with a minimum undisturbed or unaltered dimension of 10-mm diameter and 10-mm length. There presently is no perceived consensus among astrobiologists on the requirements for subsurface samples. However, for the purposes of this drilling systems analysis, we will assume that the systems should facilitate the taking of one sample per meter of depth with a high expectation that a minimum of 200 samples will be acquired, and a high probability that 50% of the samples (100) will be undamaged and uncontaminated (as defined below) when they are deposited for analysis at the surface. This sample packaging and archiving is assumed to be a **legacy technology** that will be developed for terrestrial bio-sampling research and Mars near-surface sampling missions, and will be adapted and resized for the Mars shallow sampling mission. Therefore, it is assumed that the details of this subsystem are beyond the scope of this work except that systems analysis and selection must consider and weigh the compatibility of the penetration and bore stabilization systems with sampling.

1) **Coring method.** The sampling system shall be compatible with collection of samples by rotary/percussion coring of consolidated rock, punching of fine to medium grain unconsolidated soils and collection of a single, individual particle of gravel or highly fractured rocks.

   a) **Core size**. The minimum volume of the packaged core will be 1500 mm^3. The cores are assumed to be cylindrical with a minimum diameter of 10 mm and lengths of 20-

100 mm. Either bottom coring or sidewall coring may generate these samples. We assume that any surface contamination from the core tooling and any drilling fluid that might be used is acceptable in the core extraction and packaging process.

b) **Coring containers**. The baseline coring assumption will consider that samples will be cut or punched and extruded into a thin-walled, metal sample container that will be mechanically deformed to produce a very low differential pressure, airtight seal and then transported to the surface. Generic requirements to deploy and support this capability will be produced and used to evaluate sampling systems; however the core packaging and sealing and any sub-sampling of core at the surface are beyond the scope of this study.

2) **Coring requirements.**
   a) **Bottom-hole coring**. Bottom-hole coring precludes additional samples at the same depth or shallower depths, but is very likely to be much simpler to produce samples in very small diameter boreholes.
   b) **Sidewall coring.** Sidewall coring presents a much higher risk of losing the well bore access below the core depth, and is best performed after drilling and logging are completed, and should be conducted from the bottom of the hole to the surface.
   c) **Biological contamination**. The sampling system shall preclude biological contamination of the samples to the extent that disinfecting of the core cutters, punches, and formable metal containers are accomplished by sterilization to Viking standards before launch.

3) **Maintain in situ conditions.** The sample will be exposed, packaged, transported to the surface, and deposited in a surface depository. The unaltered inner core of the sample will experience no more than a 10 degree K change in temperature and a change in pressure not to exceed 10 times the normal barometric fluctuation. The depository is assumed to be part of the sample analysis system and not part of the sampling system as defined herein, and is therefore beyond the scope of this analysis; however, it will be included in weight estimates in a notional way.

4) **Chemical contamination**. Reducing the temperature of the rock cutting process used to expose and remove the core to the minimum practical temperature will minimize chemical contamination of the core. Potential contaminates from the core cutter and sample container will be limited to: 1) elements and compounds found in high strength alloys and carbon steels, 2) silicon carbides and diamonds used in hard-rock cutters and candidate thin metal containers and foils, and 3) any cutting fluid that may be used.

Preliminary Mission Constraints and Resources

In this section, we list the assumed mission constraints that are needed to evaluate the drilling/sampling systems. These assumptions are not based on any detailed mission design, but are thought to be reasonable and within the class of missions likely to support the shallow sampling objectives. Many of the constraints we list were not used directly in the analyses, but are included for completeness, and as a basis for further study, definition, and analysis.

System Mass
Total system mass should not exceed 250 kg for the penetration and sampling systems.
1) This Martian lithosphere-penetration system includes the following subsystems:
   a) Rock and soil comminution

   b) Drill conveyance
   c) Cuttings disposition (transport and/or injection)
   d) Well bore stabilization
2) Power management
   a) Storage and surface conversion (not considered on the long list of drilling systems)
   b) Downhole transport
   c) Downhole conversion
   e) Process monitoring and control
   f) Thermal management
   g) Reconfiguration after landing system has landed on the Martian surface
3) Sampling and scientific measurement systems include:
   a) Sample coring and preparation
   b) Sample transport
   c) Down-hole scientific sensing
4) Elements of the penetration, sampling, and sensor systems that are NOT considered on the long list of systems include:
   a) Communication systems (except from surface to BHA)
   b) Power supply
   c) Energy storage to support non-sampling system function
   d) Surface-sample handling devices to store samples at a proper temperature, remove the sample from the container, and analyze the samples
   e) Thermal management for these subsystems

Power and energy consumption

All dimensions are in mm/in.

4526
(178.2)

3749
(147.6)

4366
(171.9)

775
(30.5)

4-m dia

Delta III 4-m

Figure 2. Delta III payload fairing (Boeing Corp.)
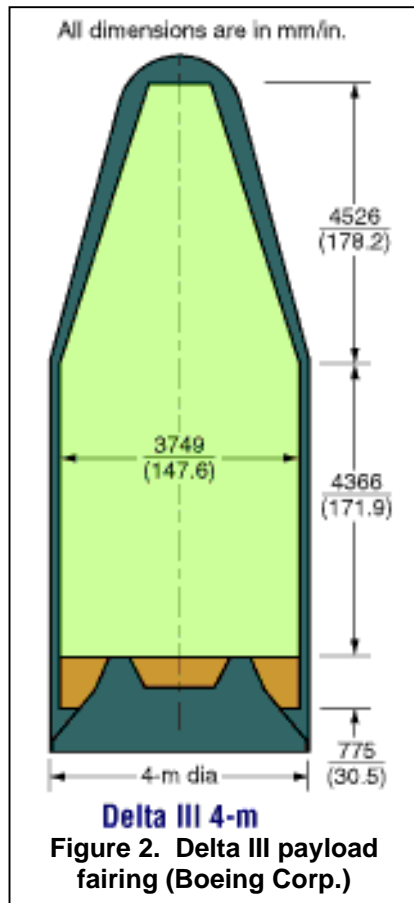
System energy requirements shall not exceed 1.0 kW hours per Sol.

Systems based on continuous operations are assumed to require less than 40 watts average power. A conceptual energy accumulation and storage system will be included in the drill system mass. Systems based on daylight operations are assumed to require less than 80 watts during operations and 5 watts during secured standby time. A small conceptual energy accumulation and storage system will be included in the drill system mass.

Packaging envelope

Lander will be compatible with Delta III fairing.

It is assumed that the packaging envelope for transport must be accommodated by a Delta III launch vehicle fairing (Figure 2). The approximate packaging volume is assumed to be a conical frustum with a base diameter of 3 m, a height of 3 m, and a top circle diameter of 2 m. Mars aerobraking and descent details were not considered except that the lander described below is sized to allow some volume for an aeroshell within the Delta III fairing.

The dimensions of the power supply, communications systems, and analysis systems are not estimated or constrained at this time.

Environmental extremes during transit are assumed to be:
- i   Temperature: 100 K to 300 K.
- ii Maximum sustained acceleration = 4 gees.
- iii Maximum radiation not determined.

Duration of the sampling process

Drilling and sampling will be completed within 200 days of landing and deployment.

The drilling and sampling process should not exceed nine months, excluding long term geophysical monitoring that should be maintained until data transmission ceases. Allowing for some margin, we will assume that the drilling and sampling must be completed within 200 (Mars) days after landing and deployment, implying an average penetration rate of 1-m/day.

Command and control, and monitoring requirements

Command and control of the system are assumed to be autonomous. All processes must be very well suited for automatic, unattended control.

Systems must (1) be fault tolerant and (2) provide redundancy/self repair for reasonable contingency situations.

All processes must be readily monitored with a few rugged and reliable sensors that are suitable for operations on the Martian surface and/or subsurface.

All processes require a fail-safe shut down mode if unexpected conditions are experienced or monitored process variables fall outside of expected ranges. To survive Martian dust storms, the design must allow for up to a 70-day-long, low-power, safe-mode shut down.

Stored command sequences may be updated no more frequently than twice daily.

1) A round trip time communications delay of 40 minutes is assumed.

2) Direct communications with Earth will be limited to only one half of each Martian day (~ 24.7 hours) and generally will not correspond exactly to the daytime portion of the Martian day.

Potential collateral resources

1) Waste heat from other processes on the lander = 1kW hr/Sol.

2) Surface resources = Martian atmosphere, solar insolation.

Legacy requirements

Subsystems that are believed to be scalable to support the 4-kilometer-depth penetration and sampling system are weighted favorably in the systems evaluation process over systems that have no possible application in a deep drilling system.

Probability of mission success

The probability of mission success for the 200-m subsurface sampling mission (exclusive of encountering conditions that might cause a blow out) are very highly emphasized in the system evaluation and selection process. The practical implications of this include:

1) Modifications of mature technologies that produce the desired results are weighted favorably over advanced concept systems that presently have limited or no shallow or deep-well utility on Earth.

    a) Modifications of commercial systems are weighted favorably over research or early prototype systems based on noncommercial drilling and sampling techniques.

    b) Simple systems are rated favorably over complex systems (remembering that simplicity is a very subjective judgement based on experience as much as any quantifiable measurement or estimate)

2) Weighting of systems supports the following priorities listed in order of importance.

    a) Sense, monitor, diagnose, and communicate drilling, sampling, logging and support process failures to support redesign of future missions.

    b) Produce scientifically satisfactory geophysical logs that will be of great value in designing and testing future subsurface sampling missions.

    c) Produce scientifically satisfactory samples that will meet the science objective for the subsurface sampling program.

3) Contingency, flexibility, redundancy, serviceability, and repairability are favored over elegance, novelty, originality, and resilience.

Summary of Assumed Mission Impacts Based on Constraints and Resources

List of Implied Drilling Impacts

In this section, we anticipate the impact of the mission requirements and constraints on the penetration approaches, sampling system, and logging requirements, and produce a list of assumed impacts on the drilling systems. This is the beginning of the system screening analysis using a series of simple calculations implied by the mission objectives, requirements, and constraints to eliminate or pass specific systems on for more detailed analysis. Because of the limited scope of this project many of the constraints and assumptions listed above were not explicitly considered, but served to set a context for the analysis that follows and did affect the outcome. In future iterations, the list should be reviewed, expanded and modified, as required, and applied in a formal systems evaluation process to all systems under consideration.

Mass limitation

1) The mass limit will require a very small, by terrestrial standards, penetration hole diameter. Penetration hole size is limited to a range of 24 to 65 mm, depending on bit thrust required for the drilling process. This result is based on a preliminary calculation using the following assumptions based on terrestrial drilling experience.

    a) A maximum drill-stem OD of 22 mm is calculated if the drill stem is ¼ of the total penetration system mass = 60 kg.

    b) Surface-generated thrusting is assumed.

    c) Drill-stem-conveyed thrust below the long-column, hole-supported buckling point of the drill stem.

    d) The maximum bit thrust (WOB) for an unanchored spacecraft will be less than 2500 N and anchoring will be required for all but the very smallest hole sizes unless "low drilling thrust" drilling methods are employed. Anchoring may serve a dual purpose by providing a heat sink surface for thermal management systems.

    e) Very thin wall, low density, high strength tubulars will be required for drill stem and bore stabilizing casings, if used.

2) Transport to Mars of drilling fluids, cements, and other common well construction materials will most likely be unfeasible.

Power/total energy limitation

1) The power limit will support hole sizes an order of magnitude larger than the mass limit supports if efficient mechanical hard-rock drilling methods are used (rotary diamond kerf coring, rotary drilling, or rotary-percussion drilling).
2) The power limit will support hole sizes larger but similar to the mass limit hole sizes for low to medium efficiency hard-rock drilling; example processes are high pressure jet drilling, rock melting, electric arc, and plasma drills [4,5,6].
3) Hole size calculations assume:
   a) 1-m/Sol effective advance rate
   b) 90% efficient power conversion
   c) 33% of the total power is used for comminution

Transport volume limitation

1) Longest collapsed mast unit will be 2.5-m long.
2) Threaded-and-coupled drill-stem length, if used, will be 1-m long. This implies a requirement for at least 200 joints, which impacts tripping, and reliability.
3) Continuous tubing, if used, will be transported in a 1.5-m diameter coil.

Lithology

Drilling of highly laminated formations including a wide range of material including sand, ice, permafrost, unstable conglomerates, and very hard rock is required. The following implications follow from this assumption.

Bottom-hole and sidewall coring systems must be compatible with the maximum range of mechanical properties of samples. Core cutters and catchers must be interchangeable:

1) "Traditional" rotary/percussion core heads designed to cut consolidated rock must be considered in the design.
2) Punches, baskets, and/or bucket augers that will be needed for recovery of unconsolidated, fractured, or easily fractured soft formations must be considered.
3) High threshold thrust (WOB) may be required for mechanical drilling systems in hard rock. Total landed weight may be insufficient to produce thrust. Solution may require:
   a) Rig anchors. Martian surface at landing site may be hard rock or unstable sand dune; anchoring systems must be able to deal with either situation.
   b) Sand bags. Source of surface sand may be unavailable, filling/handling may be too complex.
   c) Cuttings collection and storage could be used to provide additional weight.
4) Low thrust drilling technology should receive a significant benefit in the system evaluation.

The drill stem must convey thrust unless drill collars or down-hole tractor or thrusters are used [7]. Drill collars are massive, stiff, near flush joint-connected tubes that are difficult to hold onto when breaking out the joints and easy to drop while inserting or removing from the hole compared to drill stem which typically has tool joints that are somewhat larger than the pipe diameter and are much easier to hold to while handling. Drill collars count against the drilling system mass limit and are no more efficient than surface thrust in 200-m-deep, near-vertical holes if drill-stem friction can be managed. Low gravity will require very long drill collar

assemblies that are difficult to assemble and impractical to handle when drilling assemblies are removed from the hole. Down-hole tractor and thruster technologies are not well developed at this time, and would aggravate hole stability problems in some rock types; more research is needed if this technology is to be pursued.

Penetration of multiple layers of hard rock separated by unstable or unconsolidated rock is required. A strong tendency for hole caving and sloughing in unsupported bores may require re-drilling of filled bore, stuck drilling assemblies, and loss of the rig due to major bore collapse. Solution may require:

1) Overburden drilling technology
2) Casing while drilling
3) Under reaming drilling technology
4) Casing advancing systems in a potentially high friction environment
5) Bore-wall stabilization system
6) Hard-rock overburden drilling capability

There is also a strong tendency for jamming and vibration-induced damage and accelerated wear of bit and bottom-hole drilling assemblies with mechanical drilling approaches. Therefore,

1) Straight and vertical holes are needed to minimize friction when using surface thrusting.
2) Straight and vertical holes eliminate key seating (cutting a groove in the side of soft formations through a bend that catches and sticks drilling assembly components larger than the drill stem).
3) Straight and vertical holes are needed to improve performance of casing advancing systems.
4) And finally, straight and vertical drilling will require active as opposed to passive control.

Porosity and Other Rock Properties

Highly permeable porous or fractured formations will very likely be penetrated. Implications include:

1) Bottom-hole and sidewall coring systems must be compatible with rock materials that induce jamming of core samples in core barrels (e.g., highly fractured formations).

2) Drilling fluids, if used, will have to be in situ gas (Martian atmosphere, or MA) because loss of imported fluids is not acceptable from a mass point of view.
   a) The annulus will have to be operated at MA pressure to maintain an acceptable fluid recovery rate.
      i. Reverse circulation will not be feasible because of mass loss to the penetrated formations below any hole-stabilization lining.
      ii. Cuttings may need to be sucked out of annulus if fluid circulation cuttings transport is used (i.e., the annulus needs to be operated at sub-atmospheric pressure).

3) Dry, cold near-surface Martian environment will very likely result in high coefficient of friction between drill stem and drilling assembly surfaces and the bore wall. Implications of this include:
   a) Strong tendency to buckle slender drill stems

    b) Friction sticking of drill-stems in tension if bore is not kept reasonably straight

    c) This will present significant difficulties for advancing the casing in an overburden drilling system. Effective casing lubricants may have to be developed that are compatible with planetary protection requirements and the Martian environment.

4) No surface pressure control will be feasible because its use would likely induce an under ground blow out and potential spacecraft collapse.

    a) Natural flow will have to be diverted and documented.
       i. Very low-pressure flow diverter on the drill stem and overburden casing
      ii. Flow line with flow meter and sampling sniffer

    b) Circulating flow will have to operate with the annulus pressure near or slightly below atmospheric pressure unless the hole is cased and sealed.

Frozen soils.

1) Permafrost and ice drilling will be required [8]. Implications of this requirement include:

    a) Bottom-hole and sidewall coring systems must be capable of cutting cores without melting the samples.

    b) Melting-induced wellbore collapse will be aggravated by gas circulation.

    c) Drill-stem-induced melting in a static, gas-filled annulus will be greatly curtailed once a gap forms between the drill stem and the permafrost surface.

    d) Thermal drilling methods may tend to induce wellbore instability due to ice melting as opposed to stability based on consolidation and rock-glass liner formation.

Logging while drilling.

1) Drill-stem-conveyed logging while drilling is required implying bottom-hole to surface data telemetry. Logging types may include:

    a) Temperature
    b) Pressure
    c) Borehole caliper
    d) Natural gamma ray or other geochemical log

Instrumented Bore.

Long-term post drilling monitoring is required and drilling methods must be compatible with installation of an instrumented completion at the end of sampling and bore logging. Examples of completions and their possible implications include:

1) Undisturbed (recovered), post-drilling temperature log.

    a) Temperature gradient measurement may require back-filling the hole with drill cuttings to prevent convective heat transfer up the hole.

    b) Thermal property measurements on recovered core samples will be needed to model the heat flow.

2) Resistivity log (incompatible with casing while drilling, or may require non-conducting casing or sensors on outside of casing).

3) Acoustic velocity log (may be incompatible with casing while drilling or require sensors on outside of casing).
4) Televiewer log (incompatible with casing while drilling).
5) Down-hole seismic array (may require backfilling of hole to improve instrument coupling to the formation).

Bottom-hole core sampling every meter.

1) Penetration system will have to support either:
   a) Efficient and very reliable insertion and removal of drill stem and coring subsystem, or
   b) Continuous coring:
      i.   with wireline retrieval, or
      ii. with surface selection and packaging of cores from long core barrels.
   c) Sidewall coring capability; requires sidewall coring system that can penetrate casing and sample behind the casing. To prevent losing the bore, any sidewall coring should be done after all drilling is completed.

Minimum core size.

1) Continuous coring systems with as small as 12-mm-hole diameter is theoretically allowed for the bottom-hole coring option.
2) Bottom-hole core sampling will require a penetration hole diameter in excess of 20 mm.
3) Sidewall coring will probably require a penetration hole diameter of 40 to 100 mm with higher values for casing while drilling and perpendicular core orientations. Bores of this diameter will have difficulty meeting mass limitations and consequently, sidewall coring is not favored over bottom-hole coring approaches.

Biological contamination

Acceptable organic materials or inorganic substitutes will have to be identified to serve as:
1) Low vapor pressure lubricants
2) Wire insulation
3) Polymer seals (o-rings and gaskets)

Maintain in situ conditions.

Downhole thermal management may present a major challenge for the following reasons:
1) Bit cooling and heat transport systems may require technology that is presently foreign to drilling systems.
2) One solution may be to maintain the bore annulus at near atmospheric pressure, and circulate or fill with MA and no additives.
3) Drill stem and casing lubricants to minimize frictional heating that are innocuous from a bio-detection point of view must be identified and tested.
4) Dissipation of comminution energy and any down-hole power conversion (e.g., electric motors) will tend to raise the temperature of the bore wall, possibly inducing instability, and raise the temperature of core samples, possibly beyond astrobiology requirements.

Preliminary Conclusions:

Fundamental Impact: Borehole diameter is mass-limited not power-limited.

Fundamental Impact: Borehole stability issues and mass limitation make hole support using anything but in situ materials questionable unless significantly smaller hole diameters are used, thereby increasing coring risk.

Fundamental Impact: Traditional terrestrial water or aqueous mud drilling is not feasible.

Analysis Approach

Comprehensive Survey of Credible Drilling Systems and Subsequent Screening

Our approach to conceptual systems analysis of the 200-m-depth Mars drilling mission is to first construct a comprehensive list of all drilling systems known to us that might possibly be applicable to the task as defined above. The result is named the LONG LIST. We have tried to be inclusive in constructing this initial listing of systems and hope not to have missed any credible approaches. The LONG LIST is presented below as an Excel spreadsheet along with the main characteristics of each system.

The next step in the analysis was to perform a first-order screening of the LONG LIST using a pass-fail criterion relative to the mission requirements and constraints, supported by simple calculations and engineering judgement. Our logic in making the initial screening decisions is given below in the form of an extended outline and associated narrative. The result of this first grading was to produce a SHORT LIST of systems for a more detailed analysis and comparison. We tried to be generous in passing systems to the SHORT LIST, but had to reduce the list to a manageable number, given the limited resources for this study and the very limited or nonexistent drilling performance documentation found for most of the systems.

Aided by analytical and numerical models to a limited extent, we then performed more detailed calculations on specific aspects of SHORT LIST systems and subsystem elements. Whenever possible, we tried to identify common subsystems, analyze these, and apply the results to generic classes of approach or individual systems when necessary. Literature searches were performed to develop detailed descriptions of systems and subsystems, and to obtain operational data and experience descriptions, if available. We searched the oil and gas, mining, ceramic machining, and trenchless-utility industry literature, civil engineering, defense applications, academic research and any other area we could think of that might have relevant data. The search was extensive but not exhaustive. We did not use proprietary or classified sources in the analysis although some of this was available to us. Considerable engineering judgement was needed at this point to visualize adaptations of terrestrial drilling systems to Martian conditions. We were plagued throughout this stage of the analysis by a general lack of quantitative and/or complete operational data on systems or prototypes. We did not attempt to analyze several theoretical concepts for this reason, but instead favored systems for which we could find adequate data. This inevitably led to a biased screening, but was in line with our objective of favoring demonstrated capabilities over unproven concepts. Other study groups may wish to examine theoretical or untested systems; we did not choose to do so, and see no reason to do so until the applicability of well tested approaches is understood.

Originally, we planned to develop a numerical weighting scheme to use as a semi-objective method of selecting and prioritizing the best systems. A weighting system was not produced or used for two basic reasons. First, we could not find complete enough data sets on enough systems to allow inter-comparisons, and we did not find theoretical, "first principles" models of the physics of rock penetration processes that would allow an objective inter-comparison among different approaches. Second, the number of systems that comprised our final list was easily reduced to three example systems without resorting to any complex scoring exercise. So-called "specific energy" has been used by some researchers to compare drilling systems, but we do not find it to be a satisfactory measure. Specific energy is not a material property but is really a process energy that has been defined in the literature in different ways by different authors. Specific energy depends on a myriad of factors [9, 10] including rock physical properties, comminution mechanisms, specific process variables such as cutter design, rotation rate, WOB, effectiveness of cuttings removal and a host of others. Change one variable and the specific energy changes. Therefore, this parameter cannot be used as the basis of a quantitative weighting algorithm but only as a general guide; for example, systems characterized by lower process energy consumption are generally preferable to those that use more energy, all else being equal. There is ongoing research in academia (and presumably industry, although this is likely to be closely held for the competitive advantage it can represent in the market place), but we are not aware of any satisfactory method of inter-comparison even within the mechanical drilling area. We used specific energy or process energy in our analyses when that was all that was available, but only in a general, non-selective way.

As a result, our detailed analysis tended to focus on subsystems and generic approaches rather than specific drilling systems. In the end, we describe and prioritize drilling/sampling subsystems. These subsystems can be mixed and matched in matrix fashion to produce a number of specific systems that cannot easily be compared at this point due to a lack of relevant data on the performance of these systems under Mars-like conditions. However, to further illustrate what an optimum system might look like, we have put together three EXAMPLE SYSTEMS that embody most of the range of possibilities. We describe these configurations below in some detail to illustrate how tradeoffs might be made.

Long List of Systems

[Refer to associated Long List.xls spread sheet]

Coarse Screening of Long List Systems

Outline of Removal and Reorganization Process

The following is an extended narrative of the screening process.

Eliminate Drilling Techniques on the LONG LIST

Drilling Fluids

Action: Remove all techniques based on a liquid or supercritical fluid circulation used to remove drill-cuttings, lubricate and/or cool the comminution process, or produce an environment for comminution.

   1) Justification.

a) The potential for high fluid loss precludes hauling fluids to Mars because of mass limitations.
   i. No liquids commonly used for drilling fluids are stable or effective at Martian atmospheric pressure and temperatures. No suitable substitutes have been identified at this time.
   ii. There is high potential for penetration of highly porous, permeable and fractured rock and unconsolidated media from the surface to 200-m depth [1]. This precludes isolating the drill hole from the low atmospheric pressure while staying within the given mass budget.
   iii. Pressurization of the bore above Martian atmospheric pressure would most likely fail due to numerous leaks through highly permeable and fractured media.
b) Supercritical fluid jets into a very low-pressure bore will be unstable and will not achieve efficient kerf formation [11]. Also, the mass of associated high-pressure components is too high.
c) Severe contamination of scientific core samples cut in permeable layers is almost assured if non-indigenous drilling fluids are used.
d) Circulation of liquids will transfer a great deal of heat and increase the tendency to melt and destabilize frozen formations [12, 13]. Other methods of cooling the drill bit may provide better thermal management of the bore wall temperature.
e) Tailor-made fluids with extremely low vapor pressures are unlikely to be suitable as a drilling fluid and will likely introduce undesirable contaminants in scientific core samples.

2) Methods considered that might alleviate the issue.
a) Seal the bore as it is drilled using a shallow surface casing and pressure control equipment so that the bore can support the pressure needed to make candidate liquids stable.
   i. The large variety of permeable rocks that might be encountered in a shallow environment makes it unlikely that one or even two methods would be able to produce an effective seal under all the conditions that might be encountered.
   ii. Current drilling practice has failed to develop highly reliable sealing methods that cover a wide range of environments and conditions. Methods used are typically a combination of art and local practice developed by experience, and have very limited success beyond the areas where they are developed. Large amounts of materials are often used before effective seals are created. Materials used may be incompatible with drilling systems, be an unsuitable contaminant in the cores and the surrounding subsurface/surface, and may require modification or a complete change in drilling equipment used to complete the drilling and scientific coring of the bore, all undesirable aspects.
b) Use liquids that are stable under the Martian atmospheric conditions and near surface unsealed bore conditions.
   i. The only liquids identified so far that might meet these requirements are low temperature vacuum greases and lubricating oils. Organic greases and oils are unsuitable due to contamination of the core. Silicone-based mineral oils and greases may be acceptable from a contamination point of view.

ii. Fluid loss due to the hydrostatic head of the fluid column will be excessive and large masses of these special fluids would have to be transported from Earth.

iii. Dual string circulation systems that isolate the liquid hydraulic slurry from the bore with a high performance insulating material would be required to stabilize frozen formations; circulation times might be severely limited with long thermal recovery times required between circulations.

3) Conclusions.
   a) Systems based on liquid circulation and hydraulic slurry transport of cuttings are not feasible without major advances in wellbore sealing technology.
   b) Systems would be highly complex and require much equipment to support a large number of contingencies that might be encountered.
   c) Drilling systems based on hydraulic liquid slurry transport and comminution in a liquid environment will be removed from the LONG LIST.
   d) Drilling systems based on maintaining supercritical fluids in the open hole annulus environment will be removed from the LONG LIST.

Systems removed include:

- 2A   Percussion churn mud cable tool drill
- 2C   Cable-deployed electrodrill [4, 14]
- 3A   Mud rotary drill [15, 16, 17]
- 3C   Mud diamond kerf coring rotary drill [18, 19, 20, 21]
- 4A   Mud power hydraulic motor drill
- 4D   Ultrasonic drill based on cavitation in a liquid drilling environment
- 8A   High pressure continuous or pulsed jet drill
- 8B   Cavitation jet drill
- 8C   Electric spark drill based on hydraulic impact cavitation
- 8E   Supercritical CO_2 jet rotary drill

Comminution Mechanisms

Action: Remove all techniques based on inability of comminution process to penetrate all required rock materials.

Action: Remove all techniques based on direct mechanical compaction.

1) Justification.
   a) Rocks including solid and fractured basalt, permafrost and ice must be penetrated if encountered [1].
      i. Direct mechanical compaction without significant cutting mechanisms is only applicable for shallow, high porosity, unconsolidated materials [22].
2) Methods considered that might alleviate the issue.
   a) None were identified.
3) Conclusions.
   a) Systems based on direct mechanical compaction are not feasible for some of the formations that must be penetrated if encountered.

b) Systems based on direct mechanical compaction might be used to produce rig-anchoring holes and/or a shallow bore though surface dunes and soil for a conductor pipe installation. The conductor pipe would stabilize the highly unstable weathered zone down to the first consolidated (and hopefully stable) layer and serve as a guide and support for the 200-m drilling system. However, mass limitations will likely preclude designs featuring more than one drilling system (on the other hand, a deep drilling system might well consider such an approach).

c) Systems based on direct mechanical compaction will be removed from the LONG LIST. Systems removed include:

- 5A   Thrust boring piercing soil drill
- 5B   Impact mole piercing soil drill
- 6A   Guided impact mole piercing soil drill

Action: Remove all techniques based on reverse (i.e., cooling) thermal spallation.

1) Justification
   a) Solid rocks including basalt must be penetrated if encountered.
   b) Spallation of basalt requires differential temperature greater than 300 degrees K and maximum differential temperatures on Mars are less than 250 K [1].
   c) Standard (i.e., heating) thermal spallation [23, 24] relies on ablation or thermal decomposition to penetrate some materials that do not spall well by a thermomechanical mechanism (e.g., limestone). Reverse spallation, by cooling as opposed to heating, offers neither of these possibilities if pure thermal spallation fails to comminute the rock.
2) Methods considered that might alleviate the issue.
   a) None were identified.
3) Conclusions
   a) Systems based on reverse thermal spallation will be removed from the LONG LIST. Systems removed include:
      i. 9D   Thermal shock reverse spallation

Action: Remove all techniques that have a fundamental incompatibility of the comminution process with the Earth-to-Mars mass transport constraint.

Comminution methods that require equipment or a resource that cannot be efficiently produced from the 1-KWH/Sol electric power source should be eliminated at this point if the mass of the resource and/or the equipment needed to produce the required drilling/sampling can be shown to exceed the mass transport constraints.

Action: Eliminate jackhammer drifter drill.

This system relies on massive, thick-wall, threaded and coupled drill steels to transmit percussive power from a surface pneumatic hammer to the bit [15, 19].

1) Justification
   a) Scaling calculations show that "drill steels" made of titanium, as a lightweight substitute for steel, will require 50% of the total mass budget for a 25-mm diameter 200-m-depth hole.
   b) Handling equipment for the drill steels will use up a substantial amount of the remaining mass budget.

c) Keeping the drifter drill does not eliminate any subsystems required by other mechanical drilling systems to mitigate the impact of the massive drill stem.

2) Methods considered that might alleviate the issue.

a) None, but drifter drills modified to reduce the mass will look much like other percussion drilling systems that have not been removed from the LONG LIST at this point.

Action: Eliminate abrasive jet drill.

1) Justification

a) Abrasive jet velocities must be very high which translates into high-pressure nozzles and massive compression equipment compared with that needed to support circulation for cuttings transport.

b) For abrasive jet drills based on single use of the abrasive, the abrasive required weighs about an order of magnitude more than the rock removed from the hole [25]. In the case of a 200-m-deep, 25-m-diameter hole in basalt this would require 2500 kg of abrasive and clearly exceeds the transport limit.

c) For abrasive jet drills based on reuse of the abrasive, the equipment to separate the abrasive will be massive and energy intensive because:

i. The density difference between the abrasive and rock will be minimal if the abrasive is suitable for basalt and within the limits of contamination constraints (e.g., garnet or corundum), and

ii. Drill-cuttings particle size distributions will vary greatly due to the large variety of material that might be encountered in the 200-m-deep hole.

2) Methods considered that might alleviate the issue.

a) Produce abrasive grit on Mars from indigenous resource. No candidate materials identified.

Action: Eliminate the rocket exhaust drill and the flame jet drill.

Since an oxidizer is not a significant natural component of the Martian atmosphere, the distinction between the flame jet and rocket exhaust drills is insignificant on Mars. Since an in situ fuel and oxidizer production plant is not part of the support system for this mission, both fuel and oxidizer will have to be transported from earth.

1) Justification.

a) Two of the rocket exhaust drills listed in [6] used fuel oil and liquid oxygen. Based on the data for the drill, the resources needed to produce a 200-m-deep, 25-m-diameter-hole in taconite (a high-silica iron ore that thermally spalls very well) would require 200 kg of fuel and oxidizer and 300-kg of cooling water or considerably less water with a 2 megawatt cooling plant. Either case clearly exceeds the mass transport limit.

b) Two of the flame jet drills listed in [6] use fuel oil and air. Based on the data for the drill, the resources needed to produce a 200-m-deep, 25-m-diameter hole in granite would require between 80 and 140 kg of fuel and oxidizer, respectively. Water usage data were not provided, but it is assumed that at least 150 kg of cooling water or

considerably less water with a 1-megawatt cooling plant would be needed. Either case clearly exceeds the mass transport limit.

2) Methods considered that might alleviate the issue.

   a) Consider electric-powered or electromagnetic-powered spallation. System 9C, microwave spallation, will not be removed from the LONG LIST with this action.

   b) Generate chemical fuel and oxidizer from the Martian atmosphere using an electric power source. It is assumed that this is technically feasible, but the plant to achieve this would use a substantial part of the mass budget and resources to feed this plant would also be massive if loss of exhaust products to the formation occurs (this assumes that the process would recycle the exhaust products to reproduce the fuel after the initially transported fuel component, hydrogen, is used up.)

3) Conclusions.

Systems based on drill steels, abrasive jetting and chemical-powered spallation should be removed from the LONG LIST because they will require more mass than can be transported to Mars. Systems removed include:

- 1A.   Jackhammer drifter drill
- 8D.   Abrasive jet drill
- 9A   Flame jet spallation drill
- 9B   Rocket exhaust drill

Action: Remove all remaining techniques that have a fundamental incompatibility of the comminution process with assumed mission energy and power constraints .

A number of remaining techniques are marginal at a 25-mm diameter hole size, but none will be removed from the LONG LIST based on energy or power constraints without more detailed calculations to estimate energy requirements.

Action: Remove all remaining techniques that have a fundamental incompatibility of the comminution process with forward contamination requirements.

No techniques are identified.

Action: Remove all techniques based on a fundamental incompatibility of the comminution and required support processes with remote, semiautonomous control requirements.

Modern sensor technology and control systems are believed to be well suited to controlling any of the remaining comminution techniques and support processes. Sensing and control will be very challenging but no techniques are identified that, on first consideration, appear to be particularly difficult to control or are, inherently, extraordinarily complex processes, except for the general borehole stability concerns. Borehole stability will be addressed as a separate issue. No techniques are identified for removal.

Action: Remove all remaining comminution techniques and their associated support processes that have a fundamental incompatibility with the downhole and Martian surface environments assumed above.

While the Martian environment is extremely challenging, none of the remaining techniques are particularly unsuited to operating in the assumed conditions except possibly for the borehole stability concerns. Borehole stability is addressed separately.

Action: Remove all remaining comminution techniques and their associated support processes that have a fundamental incompatibility with the borehole stability requirements.

1) Justification
   a) The Mission Requirements described above requires the drilling system to penetrate and stabilize formations including sand dunes, gravels, conglomerates, crater debris, and other potentially very unstable materials.
   b) Remaining mechanical drilling processes (1B, 2B, 3B, 3D, 4B and 4C) provide no effective borehole support for unconsolidated formations.
   c) Remaining thermal drilling processes that do not include the formation of a thick bore wall melt that is cast and cooled to form a liner (9C, 9D, and 10D) will be unable to stabilize the hole through unconsolidated materials. This assumes the spallation processes may partially fuse the bore wall but cannot be relied on to cast a continuous bore lining that would eliminate wall failure.
   d) Remaining thermal spallation drilling processes will be unable to stabilize the hole through any pure ice zones encountered.
      i. Permafrost and ice zones are assumed to be stable until melted and a limited duration of melting while the zones are penetrated followed by refreezing is assumed to be acceptable from borehole stability considerations.
      ii. Processes that expose these zones to long term melting are assumed to be destabilizing and unacceptable unless the melting induced by high temperature flows can be mitigated.
         • The primary advantage of spallation over melting is that it creates large particles and is potentially more efficient than melting (in theory, but not practice [6]). The large spalls require very large airflow to circulate them out and the high temperature spalls and air will destabilize frozen formations.
         • For now, extrusion of melt is assumed to be a much more compact process that can be done in a closed-loop flow system at lower flow rates and with better thermal insulation between the flow and the frozen borewall. Spallation systems should not be eliminated without more detailed analysis of the thermal management system. Melting systems will not be removed at this point.
   e) Cementing and compaction processes that occur ubiquitously in surface terrestrial sediments and soils allow the air drilling of stable boreholes below short conductor pipes in most parched areas.
      i. On Mars, poorly compacted zones can be expected to occur up to 3 times the depth they are encountered on Earth based on reduced gravity and associated compaction processes.
      ii. Mechanisms for near-surface cementing of unconsolidated and highly fractured formations cannot be assumed to be occurring in the Martian near-surface based on current knowledge. Therefore, near-surface instability commonly encountered in the top 10 m of soils, rubble zones, and highly weathered zones on Earth may exist at much greater depths on Mars.
   f) Semiautonomous control, very limited contingency options, and severely limited backup equipment (due to mass constraints) are all incompatible with high reliability

drilling through and below unstable formations with a high potential for caving and sticking of drilling assemblies.

2) Methods considered that might alleviate the issue.

    a) Reformulate the remaining LONG LIST techniques to include borehole-stabilizing features.

    b) Consider integrating the remaining mechanical drilling systems into overburden drilling methods.

        i. Mechanical drilling systems that are compatible with overburden drilling should be added to the overburden drilling techniques.

            • Propose a new overburden drilling approach for consideration

            • Modify an existing overburden drilling method to include desirable features of similar mechanical drilling methods to produce several variations of that overburden drilling approach.

        ii. Mechanical drilling systems that are incompatible with overburden drilling should be removed from the LONG LIST

    c) Consider modifying thermal drilling processes that do not presently emphasize or assure a bore wall liner formation to include that feature.

        i. If liner formation is compatible with a thermal drilling method, propose a modified drilling method for the SHORT LIST.

        ii. If liner formation is incompatible with a thermal drilling method, eliminate the technique from the LONG LIST.

    d) Reconsider arguments that borehole instability is not a problem for some drilling techniques.

        i. Except for the umbilical-deployed mole where the umbilical is fabricated at the top of the mole, no drilling techniques have been identified that are theoretically reliable in highly unstable boreholes.

        ii. Overburden drilling systems maintain hole stability by inserting a casing that supports the hole as the hole is drilled. This provides a method to reliably drill unstable formations until the casing cannot be inserted further. Continued drilling will be jeopardized by penetration of unstable material below the stuck overburden casing because the casing cannot be lowered to restrain the unstable material.

        iii. Reduced diameter overburden drilling systems can be installed inside stuck casings to extend the depth capability of the overburden system until the drill-hole size becomes too small.

        iv. Systems that install an overburden casing by fabricating it just above the drilling assembly have been proposed but have not been successfully prototyped. These systems, if feasible, would eliminate the stuck casing depth limit for overburden drilling.

3) Conclusions

    a) Mechanical drilling systems with the exception of overburden drilling systems, and the umbilical-deployed percussion mole, should be removed from the LONG LIST because they have not been shown to reliably dry-drill highly unconsolidated formations.

b) Systems removed that are compatible with overburden drilling techniques should be added back to the overburden-drilling category.

c) Systems that are incompatible with overburden drilling should be removed.

Systems removed from LONG LIST and added to the SHORT LIST overburden drilling category are:

	LONG LIST	SHORT LIST
1B.	Sonic drill mechanical vibrator [4, 27, 28]	6D alternate
1C.	Ultrasonic drill corer [29]	6D alternate
2B	Cable tool percussion churn air drill	6E alternate
3B	Air rotary drilling [30, 19]	6C alternate
3D	Air diamond kerf coring	6D alternate
4B	Air powered pneumatic motor drill	6D alternate
4C	Electric motor drill with air cooling [14, 31, 32]	6C alternate
	(Some of the SHORT LIST category assignments are rather arbitrary at this point and the category assignments are modified below as a result of more detailed analysis.)	

Remaining thermal spallation drilling systems should be removed from the LONG LIST because of incompatibility with ice or permafrost drilling. Systems removed from LONG LIST include:

- 9C. Microwave spallation drill

Short List of Systems

[Refer to associated Short List.xls spread sheet]

Analysis of SHORT LIST Systems

Technological assumptions required to perform the analysis to reduce the SHORT LIST to a final list

1) <u>Pneumatics</u>: CO_2 circulation system assumptions used to calculate pressure loss, heat transfer, and cuttings (slurry) transport in a low gravity and potentially extremely low-pressure, MA, flow loop (600 Pa) include:

a) Real gas law compressibility factors or equation of state methods.

    b) D'Arcy-Weisbach equation for turbulent flow in circular tubes will be extended to annular flow using the hydraulic radius method [26, 33].

    c) Dittus-Boelter equation for heat transfer in duct flow [34].

    d) Stokes law particle settling method for vertical bore flow [26].

2) <u>Mechanics</u>: Drag, static and sliding contact friction calculations will use textbook friction coefficients, but will use the high end of ranges, when given, to account for extremely low humidity (very dry surfaces) and greatly reduced (relative to Earth) weathering, erosion, and corrosion of surfaces and fractures in natural materials.

3) <u>Electrical systems and motors</u>: No effects due to low-gravity environment. Very low gas pressures will make cooling much more difficult.

4) <u>Hydraulics</u>: For closed-loop hydraulic systems, we list the assumptions used to calculate pressure loss, heat transfer, and cuttings (slurry) transport in a low gravity and potentially extremely low-pressure, MA, flow loop (600 Pa). Cuttings transport in a closed loop hydraulic system assumes an injection system to introduce solids into a pressurized liquid flow stream.

    a) D'Arcy-Weisbach equation for turbulent flow using the hydraulic radius method.

    b) Dittus-Boelter equation for heat transfer in duct flow [34].

    c) Stokes law particle settling method for vertical bore flow [26].

Screening of Short List to Produce a Final, RECOMMENDED List of Systems

Background

Technologies to be eliminated from the SHORT LIST to produce a final RECOMMENDED LIST are those technologies that do not meet the requirements specified in the **Mission Constraints and Assumptions** section. Technologies that were shown to not meet the requirements without detailed analysis were removed from the LONG LIST to produce the SHORT LIST. A final list, the RECOMMENDED SYSTEMS, will now be produced from the SHORT LIST using more detailed analyses and more thorough evaluations to remove systems from the list that do not meet requirements.

The following narrative outlines the process used to remove drilling technologies from the SHORT LIST to produce the RECCOMMENDED SYSTEMS. The narrative also outlines the method used to reorganize and simplify the remaining technologies to produce the final results and recommendations.

Outline of System Removal and Reorganization Process

In the following sections, we outline the analysis process by which we reduced the SHORT LIST down to a few remaining systems. The exposition of this process is somewhat tedious, but we present it here so that others can see the logic we used and the decisions we made in coming to the final results.

We begin by evaluating Sub-Component Systems that are common to a number of drilling techniques on the SHORT LIST to determine if they can be supported with the very limited mass and power budget required, or if they will function as envisioned in the Martian surface and shallow subsurface environment.

Evaluate all techniques based on energy/power requirements of the comminution process.

<u>*Technical Concerns*</u>

Based on our experience with terrestrial drilling, we anticipate that comminution is the major power sink for the drilling system.

1) Assume 200 m of solid basalt as a worst case power requirement.

2) Limit comminution to 1/3 of the total power available based on the following preliminary power budget.
   a) Comminution = 1/3
   b) Bore stabilization = 1/6
   c) Drill assembly conveyance and cuttings transport = 1/6
   d) Thermal management = 1/6
   e) Automation and control systems and sensor support = 1/6.

As we discussed above, power calculations for comminution will be very inaccurate. The reason for this is that first-principles models for mechanical comminution have not yet been derived, despite the widespread use of the concept of "specific energy"[9, 10, 35]. Empirical models work better than specific energy methods but require substantial laboratory and down-hole data at actual projected drilling conditions for drilling processes to be modeled accurately. This is a result of the fact that calculated specific energy for a drilling process is process specific and can not be relied upon to provide accurate predictions when the process is varied significantly, such as when there is a change in:

1) Rock type, in situ stress, and degree of fracturing, porosity or cementation.

2) Method of fragmentation and cutting size requirements.

3) Environment – drilling fluid, temperature, pressure.

4) Process variables – drilling rate, bit loading, rotary speed and/or reciprocation frequency.

Another concern is that most of the comminution power will be recovered by the drill assembly as heat and may have to be disposed of at the surface, increasing the power penalty for inefficient comminution. Possible ways of mitigating this thermal problem are to

1) Allow as much heat energy as possible to dissipate to the far field of the formation without challenging the temperature variation limits for sampling.

2) Calculate the power used to dissipate waste heat recovered in the well bore and include this in the total comminution power to penalize inefficient systems.

Analysis of power requirements for short list comminution systems

Lacking sufficient data to do otherwise and despite the caveats given above, we used a specific energy method to analyze the relative power requirements for comminution. Using literature values and our own experience, the estimated specific energy values for basalt are listed below in units of GJ/m^3.

1) Percussion Drill = 0.25 to 0.50 [9, 36]

2) Down-hole Air Percussion Hammer Drill = 1.3 (solid head bit) to 7.9 (roller cone bit) [37]

3) Rotary Diamond Drill = 0.6 (wet) to 1.0 (dry, estimated by adjusting the friction term, by the same ratio observed for wet and dry polycrystalline diamond compact (PDC) cutter friction [38, 39])

4) Rotary PDC Drill = 0.1 (sharp, dry, Sierra White Granite), 0.4 (worn, dry, Sierra White Granite), 1.1 (worn-out, dry, Sierra White Granite) [38]

5) Rock melting drill = 10.6 (Calculated value based on data for drilling tuff and corrected for reduced porosity of worst case basalt compared to tuff data.

Next, we calculated hole diameters if 1/3 of power budget is dedicated to making hole and 90% of that power is converted to mechanical power (or usable heat for the rock melting drill). In the case of continuous coring, we assume that the core is 15-mm diameter, and the continuous hole diameter below the reamer is that which can be achieved after a main drill creates the 15mm core hole.

	Drilling Method	Hole-Diameter For Coring Casing		
		Drill-Hole-Bottom Core	Continuous Below Reamer	Continuous Core
a)	Mechanical Percussion	$D_h = 55$ mm	$D_{cc} = 57$ mm	$D_{ccOBD} = 47$ mm
b)	Pneumatic Percussion	$D_h = 6$ mm	$D_{cc} = 20$ mm*	$D_{ccOBD} = 16$ mm**
c)	Hydraulic Percussion	$D_h = 27$ mm	$D_{cc} = 32$ mm	$D_{ccOBD} = 27$ mm
d)	Rotary Diamond Drill	$D_h = 37$ mm	$D_{cc} = 40$ mm	$D_{ccOBD} = 33$ mm
e)	Rotary PDC Drill	$D_h = 35$ mm	$D_{cc} = 38$ mm	$D_{ccOBD} = 32$ mm
f)	Generic Mech. Drill	$D_h = 37$ mm	$D_{cc} = 40$ mm	$D_{ccOBD} = 33$ mm
g)	Rock Melting Drill	$D_h = 12$ mm*	$D_{cc} = 19$ mm**	
	* Hole too small for acquiring cores of the required size; does not meet specification. ** Not feasible because kerf is too thin when core size requirement is met.			

In addition, we assume the following mass and energy penalties for continuous operation.

1) Mass of batteries will be 4 kg based on the assumption of batteries providing 100 W hr/kg.

2) Power penalty will be 20% for charging and discharging inefficiency of the batteries.

3) Reduce hole diameters by 10% if continuous operation is required.

4) Penetration rates should exceed 0.162 m/hr so comminution can be accomplished during maximum solar window.

Conclusions based on energy/power requirements for comminution

1) **Rotary, percussion, and combined rotary-percussion drilling systems will all produce an adequate hole in solid basalt to meet the requirements for a 10-mm diameter, bottom-hole core.**

2) **Downhole pneumatic percussion hammers are marginal, but should not be removed from consideration based on power concerns alone.**

3) **Down hole hydraulic hammers will produce an adequate hole in basalt.**

4) **Rock melt drilling does not meet the requirement unless significantly more than 1/3rd of the total power is dedicated to drilling, but should not be removed from**

consideration based on power concerns alone. Rock melting produces it own hole stabilization [40] and may be justified because overburden casing has a significant mass requirement and advancing the casing will require more than negligible power. Hence, the rock melting approach may be competitive if the power constraint is relaxed somewhat.

5) **All drilling systems under consideration are expected to exceed a penetration rate of 0.162-m/hr in basalt, and battery power for comminution should be avoided unless required by other systems concerns.**

Evaluate all techniques based on energy/power required for the cuttings transport process.

Next, we evaluate the energy/power requirements for several possible cuttings transport methods, beginning with

Continuous-Flight, Hollow-Stem Auger Drill-cuttings Removal to 200 m

Technical Concerns

Auger drills have a severe depth limitation due to friction between the auger flights and the cuttings. Drilling below 350-ft (100-m) depth in soft and medium-hard formations is rarely achieved in terrestrial practice due to high torque and pullout loads [per Joe Skalski, Environmental Drilling Support, LANL, 8/10/2000]. Ignoring drilling and lift, screw conveyors for granular material are limited to 200-ft length and inclines up to 35 degrees from the horizontal due to friction (Section 10-62 [41]).

The very dry formations that are expected on the surface of Mars would likely exhibit a higher coefficient of friction than auger drills typically see on earth. The effects of low gravity that should reduce the granular hydrostatic pressure of the cuttings against the auger and bore wall may not offset this effect. Therefore, assuming a simple auger model based on screw thread mechanics [42] and coefficients of friction between the cuttings and the auger and between the cuttings and the hole, the power calculated to turn the auger (not including any power to comminute rock) is 65 watt at 200-m depth. Furthermore, using the same model assumptions, we calculate a torque value of 1400 N-m at 200-m depth, which does not include the torque to comminute rock. The estimated torque limit on the auger stem is 3 N-m for a titanium or steel auger, based on torsional strength of a scaled design of a commercial auger (30-mm bore, 25-mm flights, a 12mm by 10-mm torque shaft and a 10-mm core diameter).

The results of our model calculations are

1) A 30-mm diameter auger drill is projected to reach 10 m based on the torque limits of the auger stem.

2) A 30-mm diameter auger drill is projected to reach 130 m based on limiting its power to no more than 30% of the total power budget.

3) Auger cuttings-lift will increase the heat load that will have to be removed from the well bore.

Conclusions for Hollow-Stem Auger Drill-cuttings Removal

1) **Continuous Flight Auger Drill is not suitable for 200-m drilling due to high torque and power requirements to achieve cuttings lift.**

2) **Only if the coefficient of friction between cuttings and the auger is greatly reduced in the Martian environment would auger drilling be expected to be a good candidate for the 200-m hole. As previously stated, *increased* coefficients of friction are projected.**

Evaluate 2-m Bucket Auger for Drill-cuttings Removal to 200 m

Full length drilling augers normally lift cuttings to the surface in such a way that the cuttings are in frictional contact with the borehole wall all the way to the surface. One way to reduce torque and power for auger cuttings lift is to dramatically reduce the length of the auger using a device called a bucket auger. A bucket auger is a metal cylinder enclosing an auger screw and cuttings container. The auger screw lifts cuttings a short distance and deposits them into the down-hole container that is part of the bucket auger unit. When the container is full, the whole assembly is brought to the surface to be dumped; conveyance can be by either segmented drill string, coiled tubing or wireline, as the case may be.

Technical Concerns

Concerns with the bucket auger are similar to those for full length augers. The down-hole power and torque requirements may exceed those that can be transported or developed with a down-hole electric motor [14, 31, 32]. In addition, the trip power to raise and lower the bucket to surface may be excessive.

Results of a model similar to that used to analyze the hollow-stem, full-length auger indicate that the down-hole torque required is 0.16 N-m = 11% of the calculated aluminum shaft torque allowed and 8% of a typical ¾-inch electric motor output [43]. Down-hole power required is calculated to be 45-mW (assumes a slow motion, 2-hour-long operation to pull up to a 1-m-hole-volume into a 2-m-long bucket auger). This is 2.3% of a typical ¾-inch electric motor output [43], not including gear train losses, and is readily transmitted though 200 m of very small diameter cable. The energy needed to run and retrieve a bucket auger to 200 m is estimated to be less than 5 watt-hours or 1/2% of the daily energy budget per run. This is based on an efficient wireline run-in and retrieval system. Coiled tubing deployment will require significantly higher energy to reel and unreel the tubing and the energy required is a function of the tubing and reel diameters, coiled tubing material, and wall thickness.

Conclusions for Bucket Auger Drill-cuttings Removal

1) The model used to calculate the performance of a bucket auger is believed to produce optimistic results, but the low theoretical power and torque value obtained make the bucket auger an attractive candidate even if the calculated results are a factor 5 or more too low.

2) Coiled tubing deployment may be feasible and provide much better control of the advance of the auger than a wireline-deployed bucket. Segmented drill string deployment may also be feasible, but would require an excessive number of trips, making up and breaking out each segment, relative to the number of trips needed just for bit changes.

Evaluate Steady-State, Open-loop, Martian Air Circulation for Drill-cuttings Removal to 200-m depth

Technical Concerns and Analysis

We concluded above that the only open-loop fluid that makes any sense to consider for cuttings lift is the Martian atmosphere. Considering the likelihood of massive loss of circulation to permeable formations, importation of any fluid for open-loop use would greatly exceed mass constraints. However, even with this in situ resource, there are additional concerns that need to be addressed.

The hydrodynamics of extremely low-pressure circulation systems [44] will not be conducive to either effective particulate lift or cooling for several reasons.

First, open-loop systems will operate at or near the surface atmospheric pressure. This conclusion results from the high potential for penetration of highly porous/permeable and fractured rock and unconsolidated media from the surface to 200 m [1]. This in turn precludes isolating the drill hole at shallow depths from the low atmospheric pressure while staying within the given mass budget, based on an assumed inability to form an effective seal between the penetration system and any overburden casing advancing system with a very high-reliability method.

Second, open-loop systems will operate in both continuum flow where traditional gas dynamics applies and in slip flow, a transition between continuum flow and free molecular flow. To assess the effects of slip flow, we calculated corrected pressure losses in conduits, based on Figure 8-1, page 132, of [44]. The results were that the correction required is insignificant. We also calculated the correct particle drag for drill cutting transport, based on Figure 8-2, page 134, of [45]. Again, we found that the correction required is insignificant. Based on these results, we used Stokes' and Newton's Law relationships for particle drag calculation and conventional friction factor as a function of Reynolds number to calculate pressure losses in conduits.

Third, we had to consider compressors to circulate the mass flow required for particle lift and cooling. This was based on the concerns that power and mass requirements for compressors may be excessive. In addition, there was a concern that flow loop requirements may be incompatible with drilling mechanics.

Fourth, phase changes (condensation, precipitation (gas to solid), freezing) will complicate the circulation system. The circulation systems will very likely operate across or below the triple point of pure CO_2 (216.54K). This conclusion results from the fact that the surface temperature on Mars will likely range from 225 to 195 K for latitudes of +/-30 degrees. As a consequence, we assume in our analysis an average surface temperature of 200 K and a gradient of 15 K/km, resulting in a natural-state bottom-hole temperature 2 to 4 degrees higher than the surface temperature.

Given these concerns, we next assume that 80 W total power is available during an intermittent daylight (1/2 Sol) drilling process. Of this, 1/3 of the total, 27 W, is converted to support drilling comminution and 53 W of power is available for drilling support functions including drill-cuttings transport and other drilling support activities. Cuttings transport should be limited to no more than 13 W based on our assumed power budget given above. Assuming a 30-mm diameter bore and that a 10-mm diameter core is cut, and that the flow system operates within a 25 mm inside diameter overburden casing, then:

       Case I. Assume open hole cuttings circulation to the surface from 200-m depth. This calculation ignores the pressure and power losses across the bottom-hole drilling assembly that may be significant.

1) Mass flow of CO_2 required is 0.032 gm/sec **(0.22 gm/sec)** for 0.1-mm- **(0.5-mm-)** diameter drill cuttings to provide an optimum gas velocity (significantly greater than the falling velocity). This calculation assumes a 25-mm-ID casing with a drill stem sized to produce the optimized, concentric, countercurrent flow loop geometry.

2) The calculated pressure required to circulate the flow rate needed for 0.1-mm- **(0.5-mm-)** diameter drill cuttings with the outlet operating at 1 MA (MA = 600 Pa) pressure is 22 MA **(105 MA)** at the inlet and 15 MA **(46 MA),** bottom-hole pressure at 200 m.

   The high bottom-hole pressure causes:

   a) Potential contamination of permeable rock. For example, flow loss to a surrogate 1-m-thick, 1-Darcy-permeability, unconsolidated sand exceeds 0.124 gm/sec or 386% of the flow **(1.17 gm/sec or 522% of the flow)**,

   b) The potential for precipitation (dry ice formation) and loop plugging above 40 MA, and

   c) Inadequate velocity to transport cuttings once a permeable formation is penetrated.

       The power required to circulate the loop for 0.1-mm- **(0.5-mm-)** diameter drill cuttings is in excess of 7.5 watts **(95 watts),** assuming 90% electrical-to-mechanical power conversion efficiency.

       Case II. Assume open hole drill-cuttings circulation to a junk basket 2 m above the core bit. This calculation includes the pressure and power losses across the bottom-hole drilling assembly.

1) Mass flow of CO_2 required is 0.0064 gm/sec **(0.056 gm/sec)** for 0.1-mm- **(0.5-mm-)** diameter drill cuttings to provide an optimum gas velocity (significantly greater than the falling velocity). Assumes a 25-mm-ID casing with a drill stem sized to produce the optimized, concentric, countercurrent flow loop geometry. The mass flows required are significantly lower than those calculated for Case I because the cuttings only need to be lifted in the narrow annulus around the bottom-hole drilling assembly but not the larger annulus around the drill stem (coiled tubing).

2) The calculated pressure required to circulate the flow rate needed for 0.1-mm-diameter-drill cuttings, (Figure 3) **(0.5-mm, Figure4)** with the outlet operating at 1 MA pressure is 10.8 MA **(29 MA)** at the inlet and 9.1 MA **(17 MA)** bottom-hole pressure at 200 m. The high bottom-hole pressure causes:
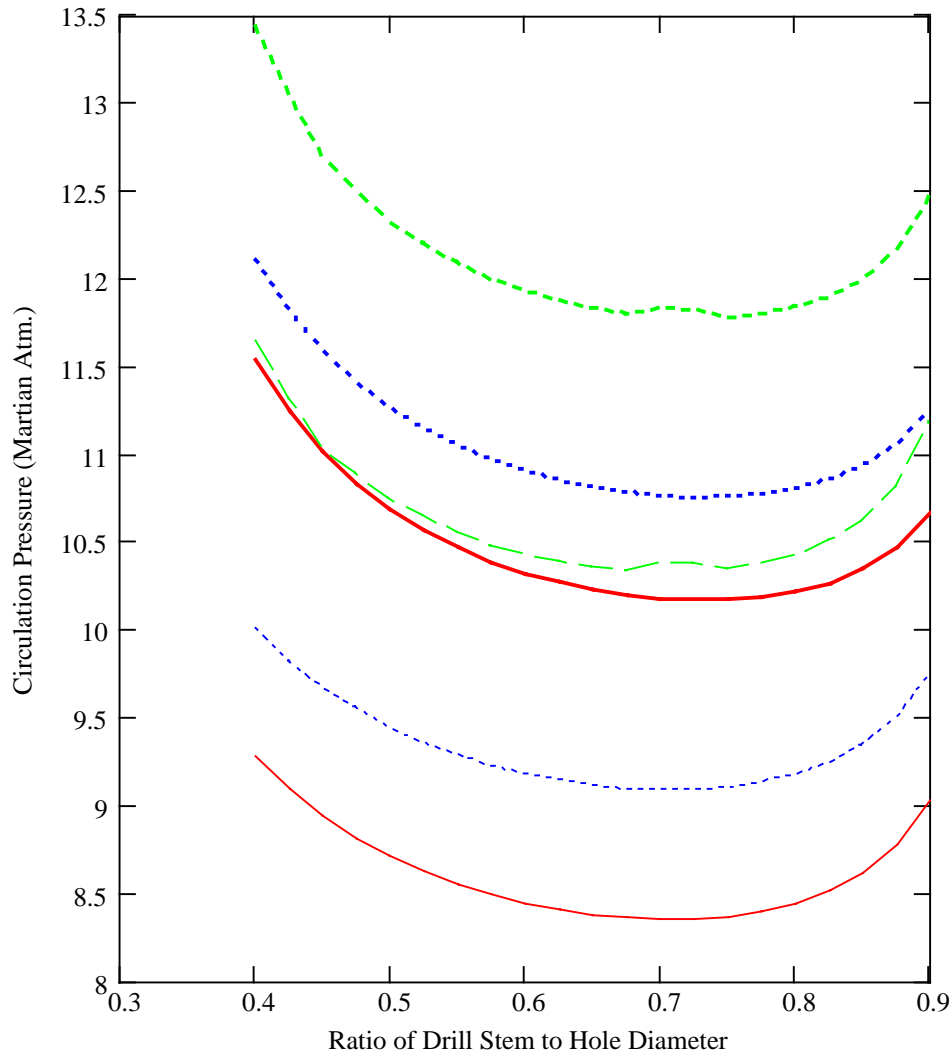
Figure 3. **Air pressure required to produce 0.0064 gram/sec open-loop airflow required to lift 0.1-mm cuttings to the top of the bottom-hole drilling assembly. Thin-lines depict bottom-hole pressure and thick-lines depict the total circulating pressure. Calculated results for various compressor suction pressures, the pressure at the top of the annular flow return:**

> **Red   (Solid) 1/2 Martian Atmosphere**
> **Blue   (Dots)   1 Martian Atmosphere**
> **Green (Dashes) 3/2 Martian Atmosphere**

a) Potential contamination of permeable rock. For example, flow loss to a surrogate 1-m-thick, 1-Darcy-permeability, unconsolidated sand that exceeds 0.045 gm/sec or 706% of the flow **(0.16 gm/sec or 284% of the flow)**; and

b) Inadequate velocity to transport cuttings once a permeable formation is penetrated.

3) The power required to circulate the loop for 0.1-mm- **(0.5-mm-)** diameter drill cuttings is in excess of 1.04 watts, (Figure 5) **(15 watts, Figure 6)** assuming 90% electrical to mechanical power conversion efficiency.
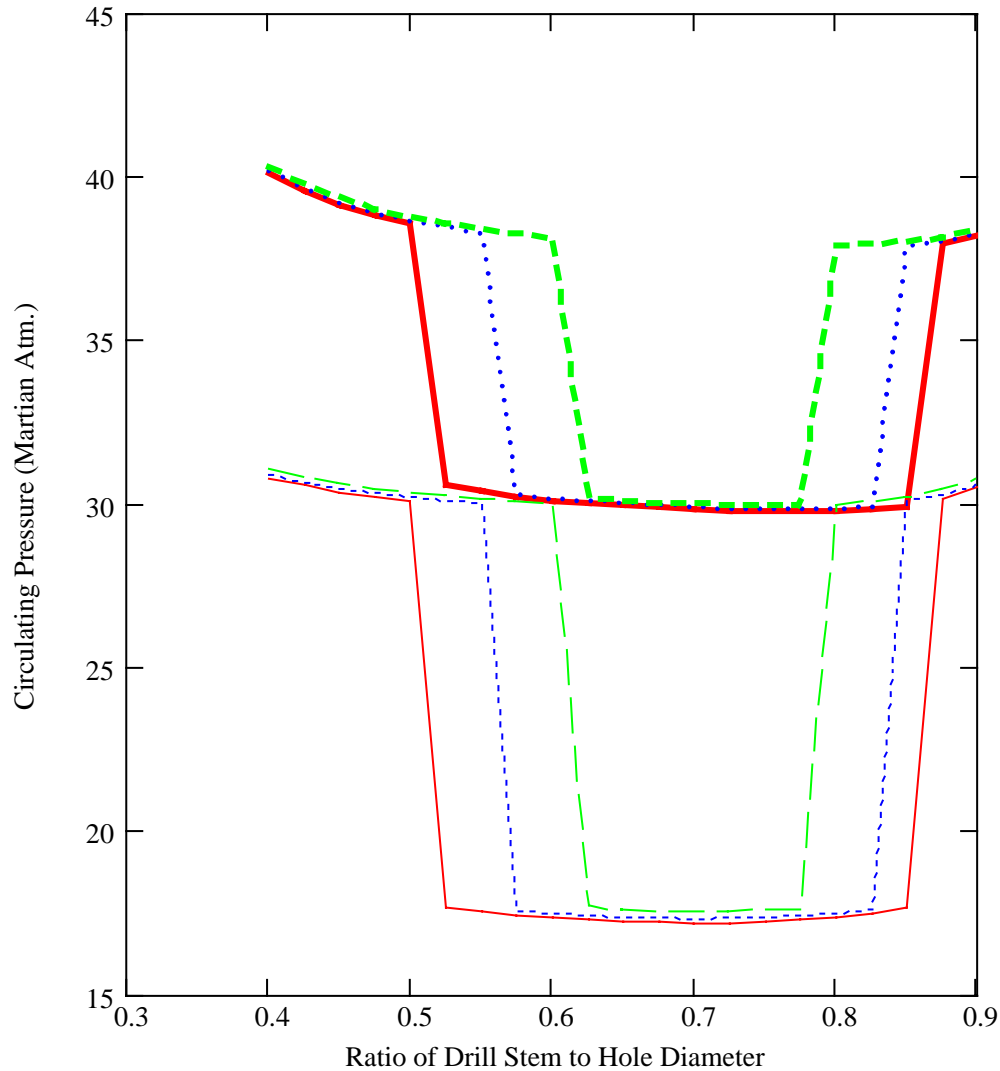
Figure 4. **Air pressure required to produce 0.056 gram/sec open-loop airflow required to lift 0.5-mm cuttings to the top of the bottom-hole drilling assembly. Thin-lines depict bottom-hole pressure and thick-lines depict the total circulating pressure. Calculated results for various compressor suction pressures, the pressure at the top of the annular flow return:**

Red (Solid)	**1/2 Martian Atmosphere**
Blue (Dots)	**1 Martian Atmosphere**
Green (Dashes)	**3/2 Martian Atmosphere**
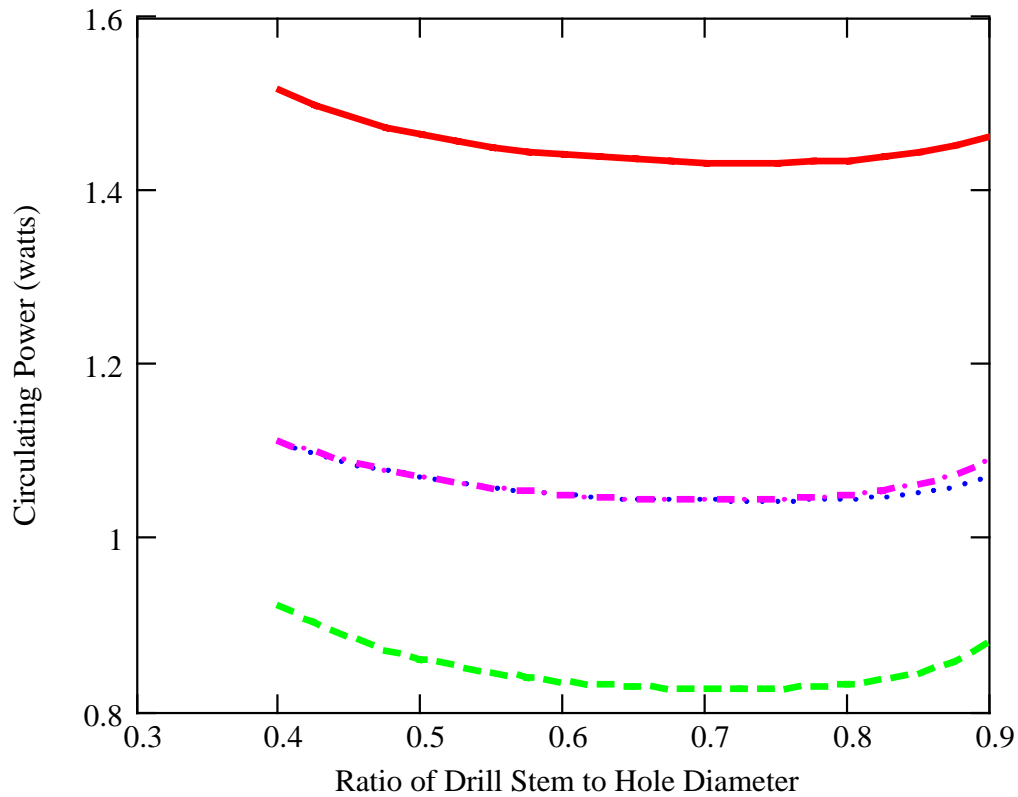
Figure 5.   **Compressor power required to produce 0.056 gram/sec open-loop airflow required to lift 0.1-mm cuttings to the top of the bottom-hole drilling assembly. Power is plotted as a function of drill-stem (outside) diameter to hole or overburden casing (inside) diameter. Calculated results for various compressor suction pressures, the pressure at the top of the annular flow return:**

Red (Solid)	**1/2 Martian Atmosphere**
Blue (Dots)	**1 Martian Atmosphere**
Green (Dashes)	**2 Martian Atmosphere**
Magenta (Dot Dashes)	**3 Martian Atmosphere**
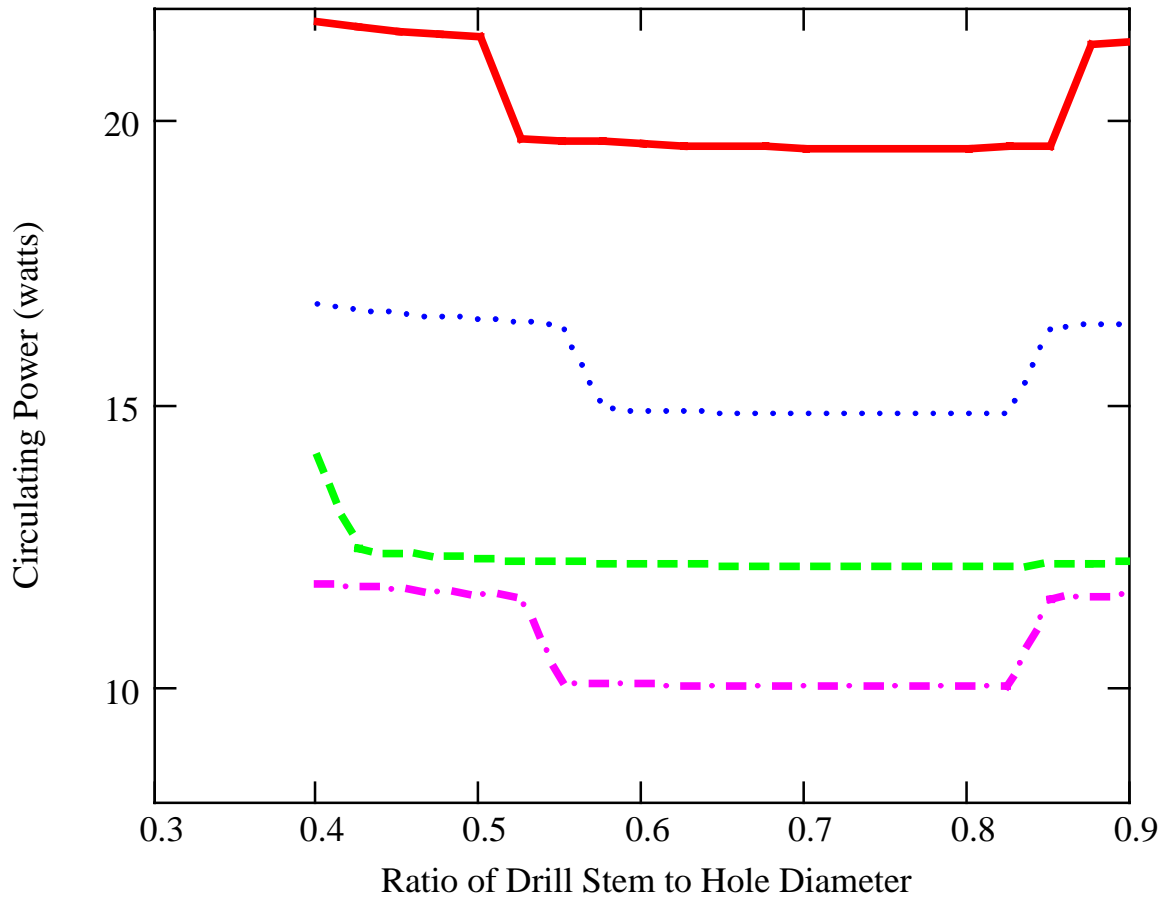
Figure 6. Compressor power required to produce 0.056 gram/sec open-loop airflow required to lift 0.5-mm cuttings to the top of the bottom-hole drilling assembly. Power is plotted as a function of drill-stem (outside) diameter to hole or overburden casing (inside) diameter. Calculated results for various compressor suction pressures, the pressure at the top of the annular flow return:

Red (Solid)	**1/2 Martian Atmosphere**
Blue (Dots)	**1 Martian Atmosphere**
Magenta (Dot Dashes)	**3 Martian Atmosphere**
Green (Dashes)	**2 Martian Atmosphere**

Conclusions for open-loop-air-drill-cuttings transport

1) **Open-loop, air cuttings transport to the surface is ruled out because the pressure required to circulate the loop and the bottom-hole pressure are too high.**
    a) **Large cuttings will require more compressor power than is available.**
    b) **Small cuttings will require a bottom-hole pressure that will produce excessive loss of circulation of air to permeable formations.**

2) **Open-loop, air cuttings transport to a cuttings basket at the top of the drilling assembly can also be ruled out because the bottom-hole pressure required to circulate cuttings to the top of the BHA is too high, and excessive air loss is predicted once a permeable formation is penetrated.**

Methods considered that might alleviate the issue.

1) Circulate the cuttings into a down-hole basket using non-steady-state circulation to produce high instantaneous flow and momentum transport (puff or air-blast).

A hypothetical system that produced an air blast for cuttings transport might accumulate high-pressure air in the drill stem. Then, a pressure-opened poppet valve would periodically blast air across the bit face long enough and with enough force to move cuttings through spiral flutes to a cuttings basket at the top of the bottom-hole drilling-assembly. In this approach, a low rate of circulation and low gas velocity in the tubing annulus should reduce pressure losses. Stored pneumatic energy should produce the power needed for momentum transport to boost cuttings up to the top of the drilling assembly. This concept looks interesting and potentially feasible, but needs to be modeled with a transient two-phase flow code and demonstrated in a 200 degree K, 600 Pa-pressure CO_2 vacuum chamber.

2) Acoustic agitated cuttings transport.

   a) Combine sonic or ultrasonic axial and rotary impulses to transfer momentum from the bit to cuttings, and clear the bottom of the hole to prevent excess regrinding and cutter dulling.

   b) Needs to be demonstrated in a 200 K, 600 Pa-pressure CO_2 vacuum chamber and evaluated.

3) Allow loss of fluid circulation and cuttings deposit into permeable formations until the formation is plugged. There is some increased risk of sticking the drilling assembly with this approach if cuttings are transferred back into the bore by a mechanical, thermal (sublimation of dry ice), or air cross-flow disturbance.

4) Combine dynamic air transport with ultrasonic or sonic agitation of the cuttings. This is a promising method that needs to be evaluated in a low-pressure/low-temperature laboratory testing program.

Evaluate all down-hole cooling (thermal management) methods based on energy/power required for the down-hole bit-cooling process.

In this section we evaluate all techniques based on air cooling of the bit using an open-loop, low-pressure, and closed-loop, high-pressure, circulation of the Martian atmosphere. We also examine closed-loop refrigeration as a suitable cooling method.

Technical Concerns and analysis

The concerns for open-loop air cooling are the same as those discussed above for open-loop air circulation for cuttings transport. For closed-loop systems, principal concerns center around mass of the systems and whether a reliable, leak-free system can be designed to meet calculated cooling needs within power constraints.

Open-Loop Air Cooling

In the analysis of an open-loop gas (air) cooling system, we make the following assumptions:

1) 80 W total power is available during an intermittent daylight (1/2 Sol) drilling process.

2) 1/3 of the total, 27 W, is converted to support drilling, and 27 W of heat is produced by the drilling assembly (15-W comminution, 12-W power conversion and cuttings transport losses) and must be removed from the borehole.

3) A 25-mm-ID casing is used with a drill stem sized to produce an optimized, concentric countercurrent flow loop, geometry.

Using these assumptions, engineering calculations give the following results, (Figure 7). First, mass flow of CO_2 required is 0.8 gm/sec for intermittent (daylight = ½ Sol) drilling, if the temperature of the CO_2 is depressed 40 K by gas expansion in the bottom-hole drilling assembly [46]. Second, with the outlet operating at 3/2 MA pressure, the minimum bottom-hole circulation pressure is achieved. Third, excessive pressure will be required to circulate this flow rate: 60 MA at the inlet, and 47 MA bottom-hole pressure at 200 m. The high bottom-hole pressure causes:

1) Potential contamination of permeable rock.

2) Flow loss to a nominal 1-m-thick, 1-Darcy-permeability, unconsolidated sand exceeds 1.35 gm/sec or 150% of the flow, (Figure 8).

3) The potential for precipitation (dry ice formation) and loop plugging above 40 MA.

4) Inadequate cooling because the assumed 40 degree K cooling will only be 20 degrees K at the higher back pressure. This makes open-loop circulation for cooling unfeasible because the power required to circulate the loop is in excess of 200 watts, assuming 100% electrical to mechanical power conversion efficiency. This is a cooling system efficiency of 13.5%, (Figure 9).

Conclusions for Open-Loop Air Cooling

Open loop air cooling is ruled out because the heat removed is insignificant when compared to the power required for removing it, and the power required is greater than the total power available. (Calculations for continuously drilling at a slow rate also show that open loop air cooling is not feasible).

Closed-Loop Air Cooling

Analysis of a closed-loop air cooling system was based on the following assumptions.

1) 80 W total power is available during an intermittent daylight (1/2 Sol) drilling process.

2) 1/3 of the total, 27 W, is converted to support drilling, and 27 W of heat is produced by the drilling assembly (15 W comminution, 12 W power conversion and cuttings transport losses), and must be removed from the borehole.

3) 25-mm-ID casing is used with a drill stem sized to produce an optimized, concentric countercurrent flow loop geometry.
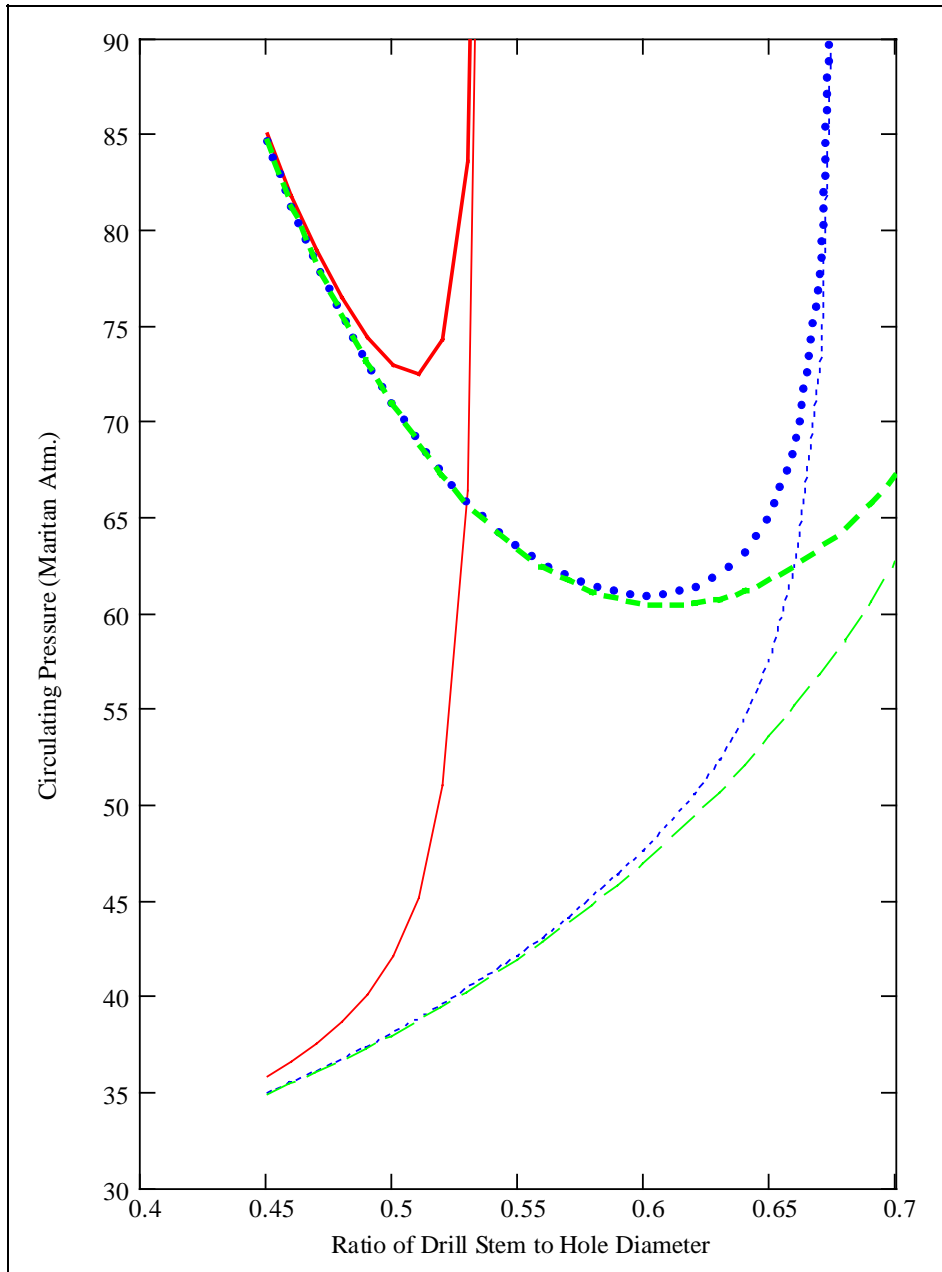
Figure 7. Air pressure required to produce 0.8 gram/sec open-loop airflow required to cool a bottom-hole drilling assembly. Thin-lines depict bottom-hole pressure and thick-lines depict the total circulating pressure. Calculated results for various compressor suction pressures, the pressure at the top of the annular flow return:

Red   (Solid)   3/4 Martian Atmosphere
**Blue   (Dots)   1 Martian Atmosphere**
Green (Dashes)   3/2 Martian Atmosphere
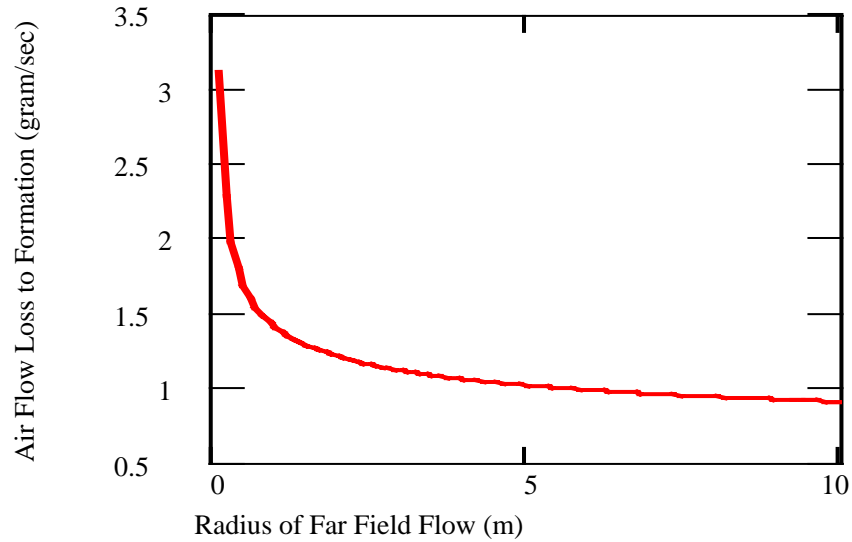
Figure 8. **Airflow loss to a 1-m-thick, 1-darcy permeability, penetrated formation as a function of the far-field, steady-state flow radius where the reservoir pressure is assumed to be at Martian atmospheric pressure.**

Using these assumptions, simple engineering calculations give the following results. First, mass flow of CO_2 required is 3.2 gm/sec for intermittent (day light) drilling if the temperature of the CO_2 is depressed 10 K by gas expansion in the bottom-hole drilling assembly [46]. Second, with the outlet operating at 80-MA pressure, the pressure required to circulate this flow rate is 180 MA at the inlet and 150 MA bottom-hole pressure at 200 m, (Figure 10). Low outlet pressures result in choked flow at rates too low to achieve the required cooling. Therefore, the high bottom-hole pressure causes inadequate cooling because the assumed 10-degree K cooling will only be 7-degrees K at the higher backpressure. Third, the power required to circulate the loop is in excess of 160, watts assuming 100% electrical to mechanical power conversion efficiency, (Figure 11). This is a cooling system efficiency of 13%, (Figure 12).

Conclusions for Closed-Loop Air Cooling

Closed-loop air cooling is ruled out because the heat removed is insignificant when compared to the power required to remove it, and the power required is greater than the total power available.
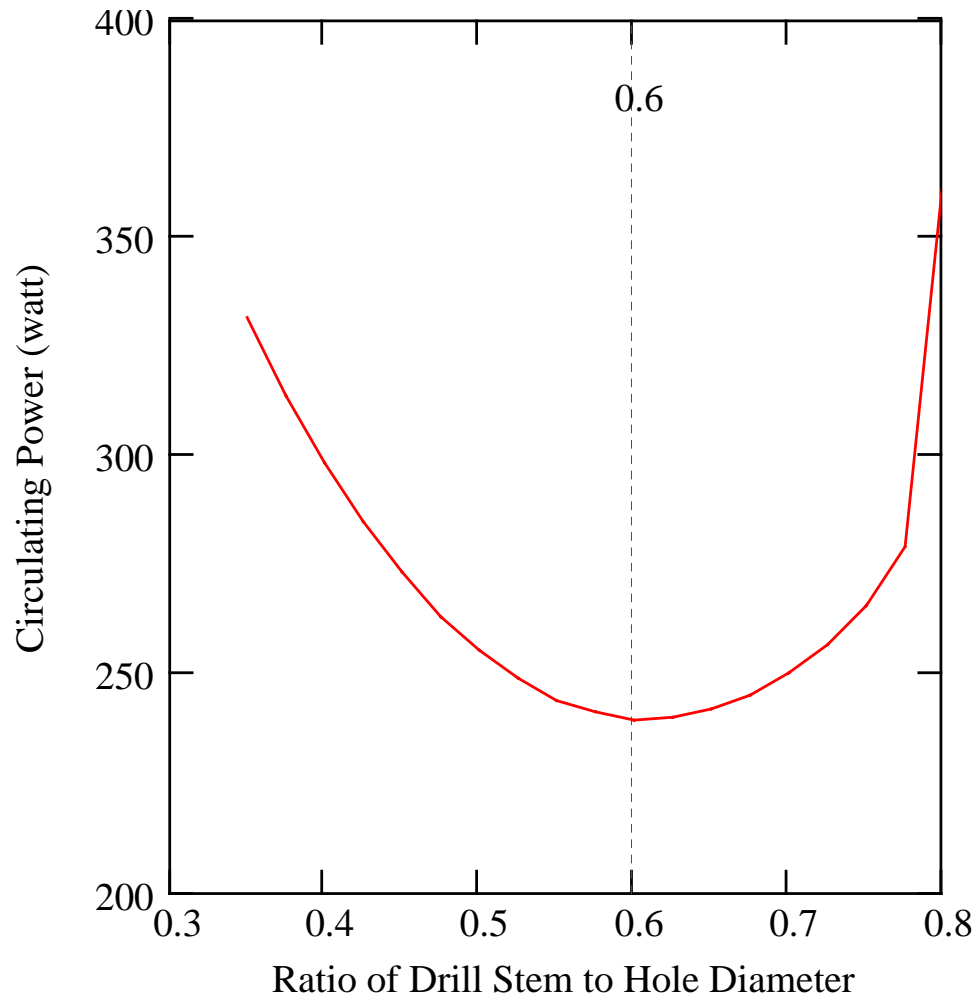
Figure 9. Compressor power required to produce 0.8 gram/sec open-loop airflow required to cool a bottom-hole drilling assembly as a function of drill-stem (outside) diameter to hole or overburden casing (inside) diameter.
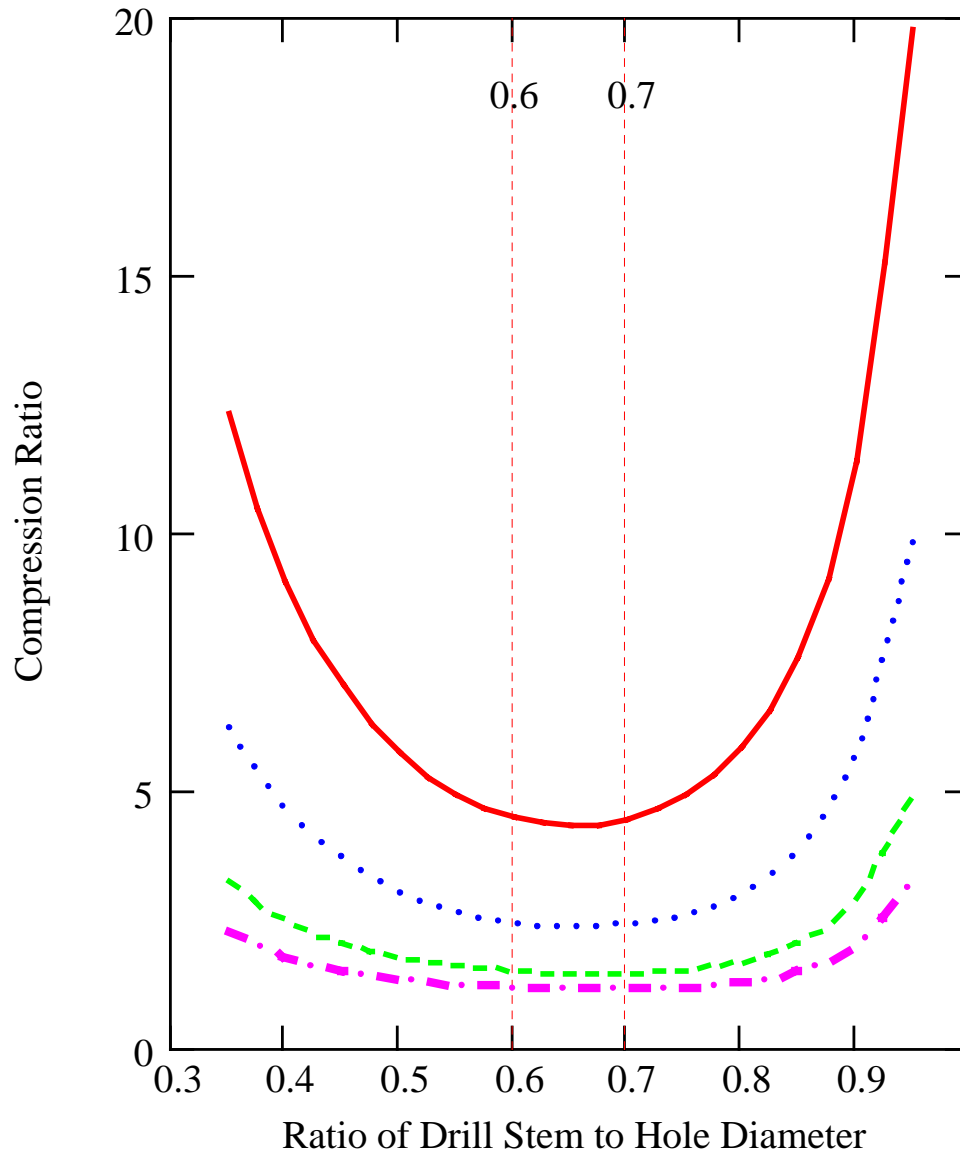
Figure 10.   Air compression ratio required to produce 3.2 gram/sec closed-loop airflow needed to cool a bottom-hole drilling assembly. Suction Pressure is the Pressure at Outlet of the Air Return to the Surface

Red   (Solid) 40   Martian Atmosphere
Blue   (Dots) 80   Martian Atmosphere
Green   (Dashes)   160 Martian Atmosphere
Magenta (Dot/Dashes) 240 Martian Atmosphere
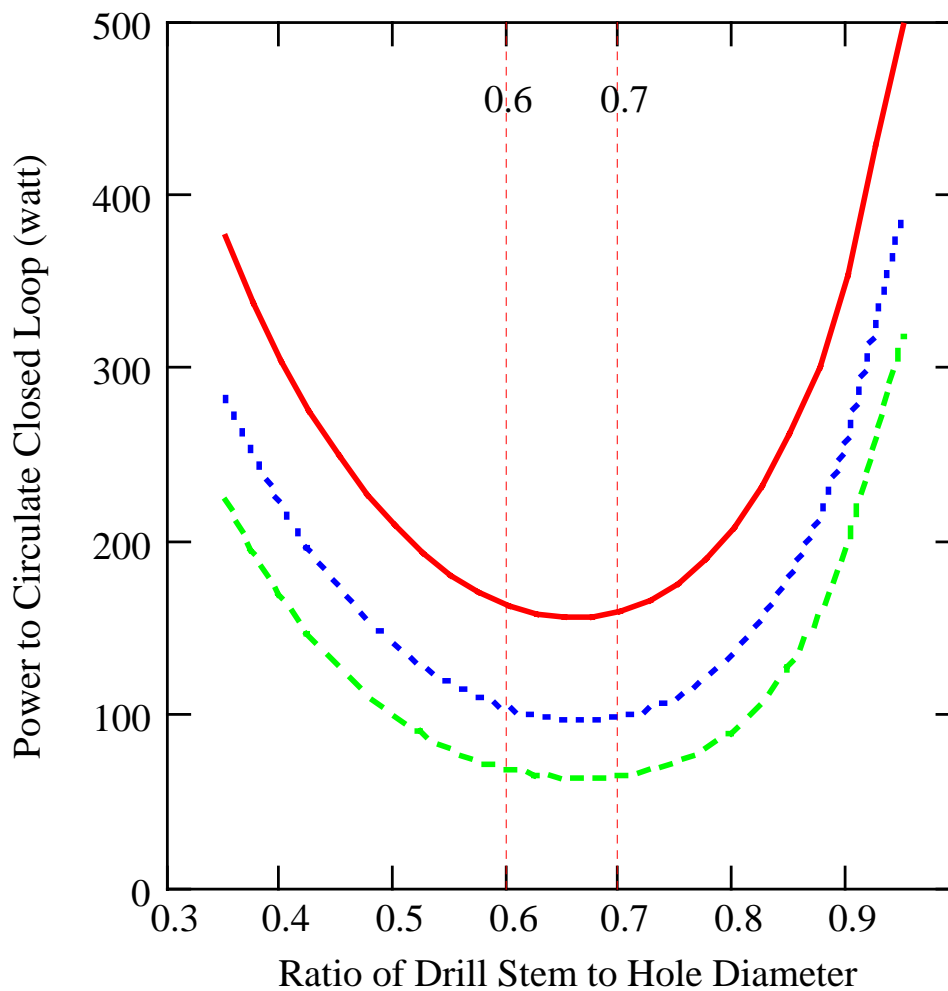
Figure 11. Compressor power required to produce 3.2 gram/sec closed-loop airflow required to cool the bottom-hole drilling assembly for various suction pressures indicated.

Red	**(Solid)**	**80 Martian Atmosphere**
Blue	**(Dots)**	**160 Martian Atmosphere**
Green	**(Dashes)**	**240 Martian Atmosphere**
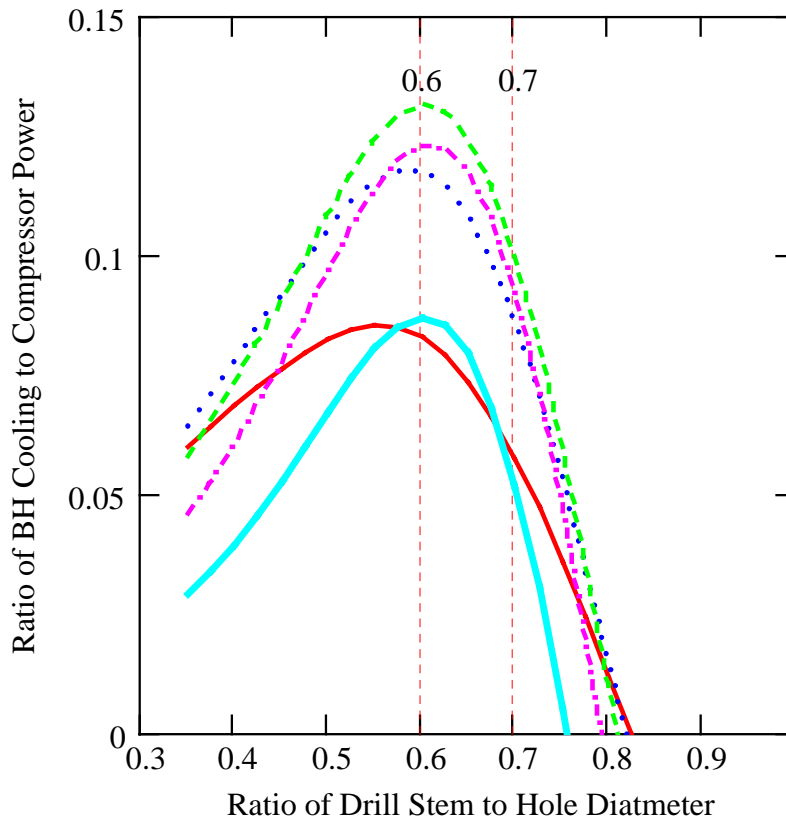
Figure 12 Cooling efficiency vs. ratio of drill-stem to hole diameter. Ratio of downhole cooling (watts) to power (watts) required to produce 3.2 gram/sec closed-loop airflow required to cool the bottom-hole drilling assembly. A suction pressure of 160 Martian atmospheres and a 0.6 diameter ratio produces the highest cooling efficiency for a closed-loop high-pressure gas cooling system.

Red   (Solid)   40 Martian Atmosphere
Blue   (Dots)   80 Martian Atmosphere
Green   (Dashes)   160 Martian Atmosphere
Magenta (Dot/Dashes) 240 Martian Atmosphere

Refrigeration Cooling

Here we evaluate techniques based on cooling the bit using a refrigeration cycle [47, 48]. Special concerns include (i) the mass of refrigerant may be inherently excessive, (ii) loss of refrigerant in the event of a leak would lead to system failure or an unacceptable mass of make-up refrigerant, and (iii) friction losses in the circulation system may lead to excessive power requirements.

In the analysis, we made the following assumptions.

1) 80 W total power is available during an intermittent daylight (1/2 Sol) drilling process.

2) 1/3 of the total, 27 W, is converted to support drilling, and 27 W of heat is produced by the drilling assembly (15 W comminution, 12 W power conversion and cuttings transport losses), and must be removed from the borehole.
3) A closed and sealed coiled tubing system is assumed to minimize the possibility of leaks.
4) A propane refrigerant circulated down a 1-mm diameter tube and up a 10-mm diameter tube is assumed.

With these assumptions, our calculations indicate that the theoretical power to operate the heat pump is 4 watts, and the power calculated for a compressor is 9 watts, ignoring circulation loop friction. The required mass flow rate is 0.068 g/sec. At the surface (no hydrostatic self-pumping), the compressor power needed for the heat pump and the circulation loop is 18 watts. The power needed is 45 watts if the heat load is doubled (e.g., concentrating the drilling time with the use of storage batteries or using a rock melting drill with 2/3, as opposed to 1/3, of the total power dedicated to hole making). We also find that, at total depth, the friction loss to circulate the system is lower than the hydrostatic differential pressure between the liquid down-flow and the vapor up-flow, so the system can be designed to be self-pumping, including heat pump power. With this approach, a compressor will be needed to start the process and to handle excess heat loads when they occur. However, if the down-hole power is doubled, the self-pumping is reduced to a break even level and the heat pump will have to be externally powered. Finally, the mass of propane that must be transported is of the order of 0.15 kg with 50% excess.

Conclusions for Refrigeration Cycle Cooling

1) **Refrigeration cooling using a low temperature refrigerant is feasible for mechanical drilling.**

2) **Since most power requirements will increase with depth, an attractive feature of refrigeration cooling is that the power requirement will diminish with increasing depth to offset the power increases of other drilling systems.**

3) **Refrigeration cooling for rock melting or other power systems that will have to operate significantly above the assumed 1/3 power split will require more power than will be available while drilling near the surface. This result, combined with calculated results in the section on comminution power, effectively rules out rock melting as a candidate for a 200-m hole.**

Passive Cooling to Surrounding Rock and Up-hole Components

In this section, we evaluate all techniques based on passive cooling of the mechanical drill bit. Passive cooling is defined to include conduction, convection, and radiation between a coring head (drill bit), core, formation, and connecting drilling assembly [49]. This method assumes that if the mechanical drilling process is operated very efficiently and very slowly, natural passive as opposed to active cooling will be adequate to cool the bit.

The main concern with this approach is that the required drill rate will be too slow to meet schedule requirements. We are also concerned that the methods used to stretch out the heat production will violate fundamental threshold requirements for activation of mechanical drilling processes. Finally, we are concerned that mission-required drill rates will overheat the core sample ($\Delta T < 10$ degrees K) or destabilize "frozen ground" (formations that are primarily frozen volatiles or granular minerals cemented by volatiles that will be highly mobilized with sublimation).

We analyzed this approach to thermal management using a finite difference Core Drill Thermal Model (see **Appendix A**). The model assumed that a core head kerf drill is used to continuously core and advance the hole simultaneously. The interface between the coring assembly and the BHA was either insulated or maintained at a fixed temperature, depending on how the core head was cooled. Bottom-hole pressure was assumed to be 1.3 MA and any gas in the hole pure CO_2. Dust (drill cuttings) in the air spaces was ignored. Specific energy of rock comminution was assumed to be 1 GJ/m^3, except where noted. The calculations assumed that the core head diameter was 30-mm-OD and 15-mm-ID, and the coring assembly was 1-m long. Bottom-hole temperature was assumed to start at 200 K, and heat generated for non-rock-breaking processes (downhole power conversion or cuttings transport) was ignored. Some results of the model runs are shown in figures 13-16. In the figures, temperature contours are shown in the core and surrounding rock near the cutting surface; the left-hand edge of each figure is an axis of cylindrical symmetry down the center of the core sample. Overall, the calculations indicated that

1) For a drilling rate of 2 m/Sol (= 1-m advance in 12 hours of drilling operations) and a BHA 1 m above the cutting surface maintained at 190 K, the maximum core temperature was 228 K and the maximum bore wall temperature was 225 K. For a case where the core head was maintained at 190 K at a point only 75 mm above the cutting surface, the maximum core temperature was 204 K and the maximum bore wall temperature was 203 K.

2) For a drilling rate of 4 m/Sol (= 1-m advance in 6 hours of drilling operations) with the core head maintained at 190 K at a point 75 mm above the cutting surface, the maximum core temperature is 212 K and maximum bore wall temperature is 210 K.
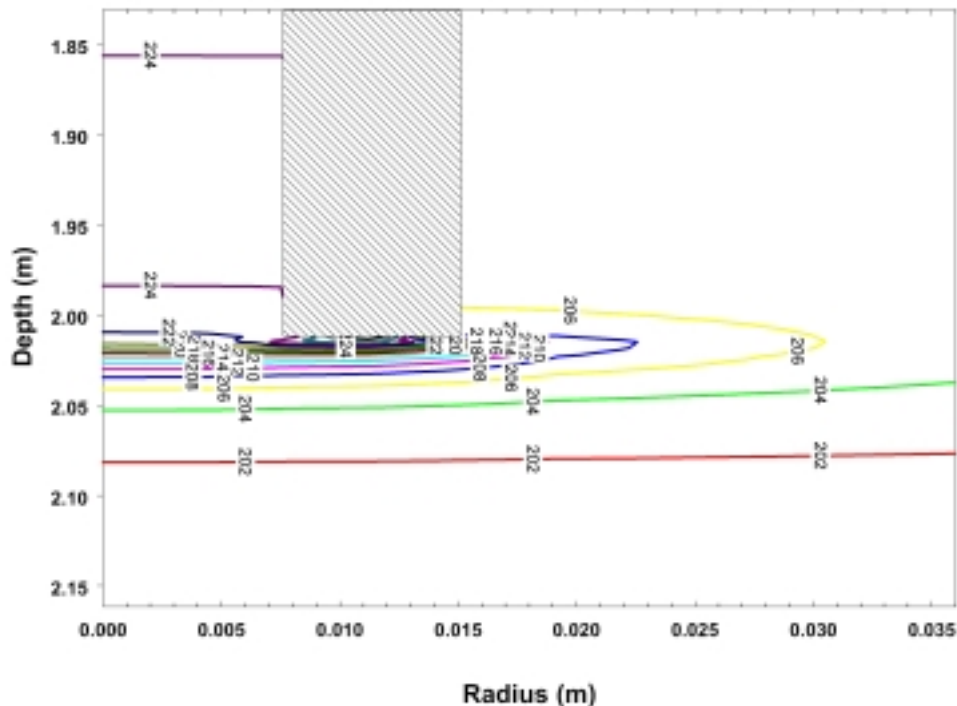
Figure 13. Coring bit temperature contours. Rate: 1 m in 12 hr, Specific energy: 1 GJ/m3, Cooling: 190 k, 1 m above the cutter.
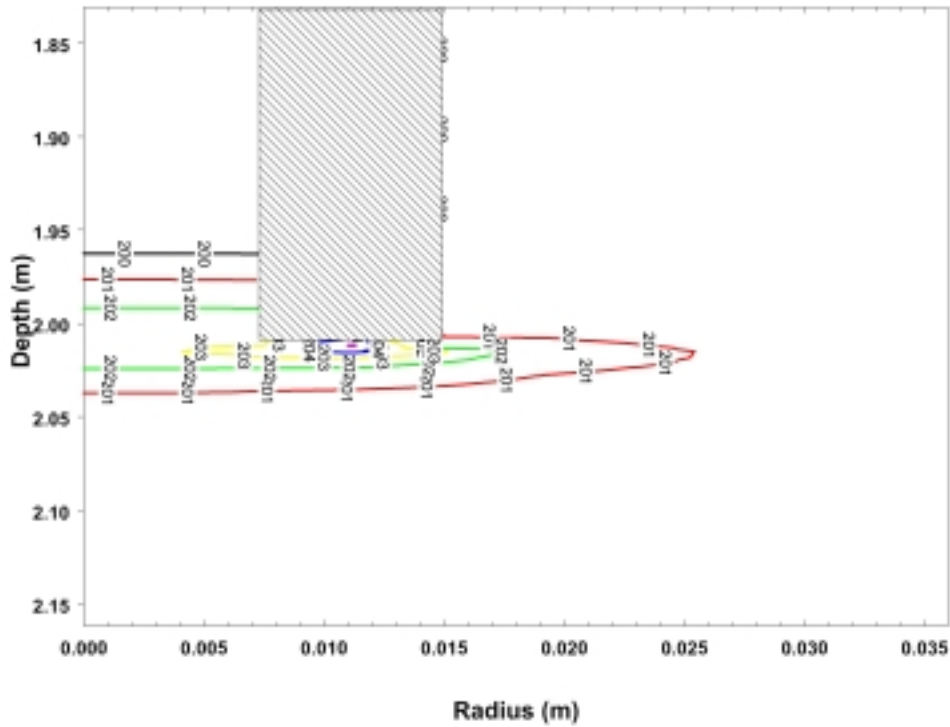
Figure 14. Coring bit temperature contours, Rate: 1 m in 12 hr, Specific energy: 1 GJ/m3, Cooling: 190 K, 75 mm above the cutter.
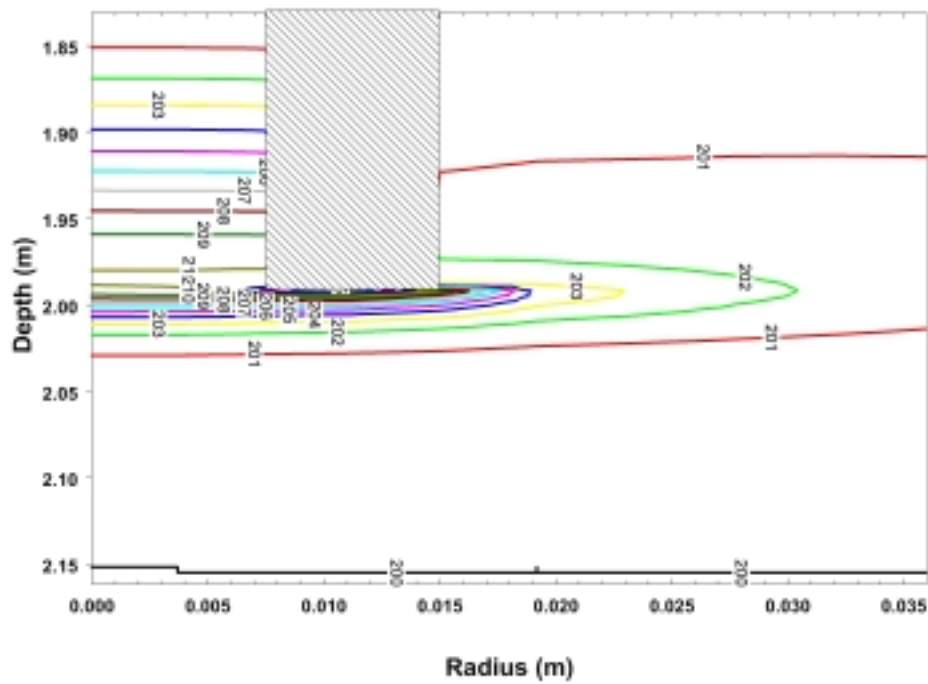
Figure 15. Coring bit temperature contours, Rate: 1 m in 6 hr, Specific energy: 1 GJ/m3, Cooling: 190 K, 75 mm above cutter.
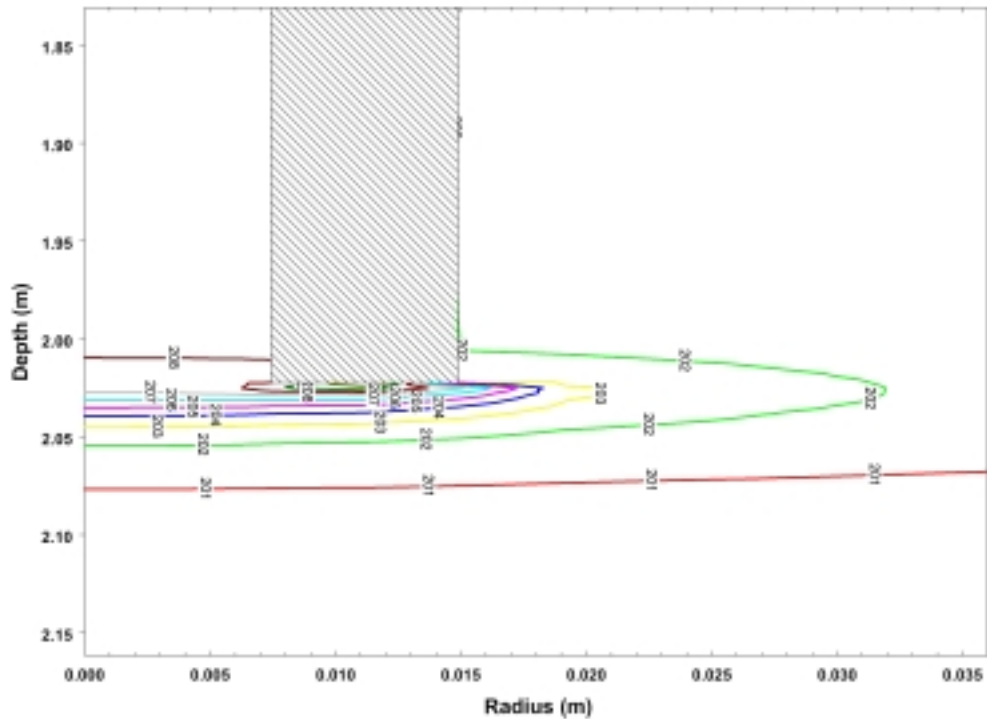
Figure 16. Coring bit temperature contours, Rate: 1 m in 12 hr, Specific energy: 1/3 GJ/m3, Cooling: no active cooling.

3) For a drilling rate of 2 m/Sol (= 1-m advance in 12 hours of drilling operations) and assuming a maximum drilling specific energy reduced from 1 GJ/m^3 to 1/3 GJ/m^3, the maximum core temperature was 210 K and the maximum bore wall temperature was 203 K.

Conclusions for Passive Cooling

1) **To avoid overheating the core sample (ΔT < 10 degrees K), cooling of the core head is required.**

2) **Nearly all of the energy expended while drilling must be removed by the cooling system.**

3) **Cooling at the top of a 1-m long core bit and relying on conduction up the bit and convection and radiation to the surrounding rock is inadequate to avoid excessive core temperatures. Cooling must be applied much closer to the cutting surface.**

4) **If the efficiency of the drilling process can be increased to the point where the rock specific energy is reduced from 1.0 to 0.33 GJ/m3, the core can be maintained below 210 K without cooling. Also, if the ΔT of 10 degrees K for the core samples can be relaxed somewhat, then passive cooling will be sufficient for managing comminution heating.**

Evaluate all drill-stem conveyance methods based on energy/power and mass constraints.

In the following sections we look at several different methods of conveying the bottom-hole drilling and sampling assemblies from the surface to the bottom of the hole as it is extended.

Umbilical Drill Conveyance

Here we evaluate umbilical drill conveyance methods including cable tool [15, 19] sand lines, flexible (non-metallic coiled tubing) structural hoses, or any other method of conveyance not designed to transmit downward thrust on drilling assemblies. There are a number of concerns and issues associated with umbilicals. Are materials of construction compatible with sampling requirements? Can umbilical systems support downhole telemetry requirements? When umbilicals are used, how can bit thrust and torque needed for mechanical drilling be provided? What provisions will be needed for replacement or repair of damaged umbilicals? Are umbilical systems compatible with hole support approaches?

Umbilicals will readily support hard wire and fiber optic telemetry cables. Technology to embed wires and fiber optic cables into composite tubulars is under development in a pre-commercialization stage (commercial products may already be available). However, materials used to fabricate sand lines, wirelines, and hoses typically include numerous organic polymeric materials that are used to separate, cushion and seal between structural strand wires that provide the required strength and pressure integrity of the umbilical and electrically insulate the telemetry wire (and power cables) embedded in the umbilical. These materials are not suitable for operations at 200 K, or in a high radiation environment. Contamination concerns may require that alternative materials (e.g., silicone-based polymers) are substituted, and special coatings and flexible metallic shields applied to isolate undesirable coatings.

Several umbilical systems have been developed to support mechanical drilling including percussion drilling and cable tool drilling methods. Technology to develop down-hole torque and thrust for umbilical systems is commercial in the trenchless utility drilling industry and is under development for deep hole applications in the oil industry. Methods include downhole thrusters [7, 50] or tractors that grip the well bore just above the bit, and inertial methods such as hammers and impact rotary motors.

The normal method for replacement or repair of a damaged umbilical is to cutoff the bottom-end of the umbilical and re-head after every few runs. Re-heading the bottom end of an umbilical is a complex operation that may not be easily adapted to robotic operation. Furthermore, provision for telemetry and internal utilities make re-heading even more difficult. One way to reduce risk of wear and damage to umbilicals to near zero is by over-design and comprehensive testing to eliminate failure and high-wear modes.

Hole support for umbilical-deployed drilling systems exists in the form of commercial drilling systems that deploy a drilling assembly to the bottom of an overburden casing-advance drilling system on sandlines and wirelines. Also, the NASA/JPL percussion mole concept is a very advanced umbilical concept that has theoretical merit.

Conclusion

Umbilical-deployed drilling assemblies should not be eliminated from the final list of drilling technologies.

Reeled or Coiled Tubing Conveyance Methods

Coiled tubing [7, 50 and 51] drill conveyance methods deploy drilling assemblies on continuous metal tubing stored on a reel. Bit thrust is produced by means of a mechanical or hydraulic injector at the surface that grips the tubing and pushes it down hole. Drilling fluids are commonly conveyed in the tubing and cuttings circulated to the surface in the annulus between the tubing and the borehole wall. Power and telemetry cables are often conducted down hole to drilling assemblies inside the tubing and commutated at the surface in the reel hub.

Concerns and Analysis

Some of the concerns that arise when considering coiled tubing conveyance of drilling assemblies for shallow drilling on Mars include:

1) The energy required to spool and unreel the tubing may be excessive.

2) The size of the reeled tubing may exceed dimensional constraints.

3) Mass of the coiled tubing may be excessive.

4) Providing bit thrust and torque needed for mechanical drilling may be difficult.

5) Repair or replacement of damaged tubing may be difficult or impossible.

6) Compatibility with hole support approaches must be addressed.

In our analysis, we first considered the power that would be required to reel the tubing. Two simple models were developed based on tubular bending energy calculations. The first, was based on an integration of the bending stress over the cross-sectional area of the tube and the second model was based on Appendix C in [52]

Case I. Elastic deformation reeling [52, 53].

If the ratio of the coiled-tubing outside diameter to the reel diameter is less than the ratio of yield stress to the elastic modulus of the tubing material, the reeling operation will operate in an elastic deformation mode. For example, titanium coiled tubing has a high yield-to-modulus ratio and will allow elastic storage of tubing with up to 12-mm-OD. In theory, the reel can also serve as an energy storage device, but power will have to be applied to either reel or unreel the tubing. The calculated power to reel straight tubing (a function of diameter to thickness ratio (D/t) and diameter) is:

1) 3.5 watts (**4.0 watts, model 2**) for 10-mm diameter titanium (D/t=20) tubing on a 1-m diameter reel at 10 m/min round-tripping BHA rate.

2) 0.48 milli-watts (**0.56 milli-watts, model 2**) for 10-mm diameter titanium (D/t=20) tubing on a 1-m diameter reel at 2 m/Sol drilling advance rate.

Case II. Plastic deformation reeling

If the ratio of the coiled-tubing diameter (OD) to the reel diameter (ID) is greater than the ratio of yield stress to the elastic modulus, the reeling operation will operate in a plastic deformation mode. For example, aluminum coiled tubing has a moderate yield-to-modulus ratio and will require plastic storage of tubing with a diameter as small as 12-mm OD. Present practice [54] calls for steel coiled tubing to be shipped and stored on reels with a reel-ID-to-tube-OD ratio of between 34 and 48. Where a large number of reeling and unreeling operations are required, a ratio as low as 20 has been used. Assuming elongation is the major factor determining the ratio and aluminum tubing with elongation of 12 [55] as compared to 30 for steel coiled tubing [54], aluminum tubing will require a reel-to-tube diameter ratio of about 60. Power

to deform the tubing will be required to both reel and unreel the tubing. Calculated power to reel straight tubing is:

1) 11 watts (**7.8 watts, model 2**) for 15-mm diameter aluminum (D/t=20) tubing on a 1-m diameter reel at 10 m/min round-tripping BHA rate.

2) 1.5 milli-watts (**1.1 milli-watts, model 2**) for 15-mm diameter aluminum (D/t=20) tubing on a 1-m diameter reel at 2-m/Sol drilling advance rate.

The size of a reel to hold 200-m of titanium or aluminum [the size of the reel is not affected by the material choice, but the mass is] tubing is:

1) A 10-mm-OD tubing reeled on a 1-m core requires a width of 210 mm and an OD of 1.1 m. Allowing 110% multiplier for the thickness of the reel, this easily fits within a 1.5-m diameter cylinder.

2) A 15-mm-OD tubing reeled on a 1-m core requires a width of 230 mm and an OD of 1.15 m. Allowing 110% multiplier for the thickness of the reel, this easily fits within a 1.5-m diameter cylinder.

Calculated Masses of coiled tubing are as follows. 200 m of 10-mm diameter titanium tubing has a mass of 14.5 kg. 200 m of 15-mm-aluminum tubing has a mass of 18.8 kg.

Thrust and torque can be applied by coiled tubing, but the small tubing diameters under consideration and the plan to drill a perfectly vertical trajectory will limit thrust to very low values and the torque to moderate values. The same technologies used to apply thrust and torque in an umbilical drilling system can be readily applied to coiled-tubing.

Cutting out and repairing a bad area of the coiled tubing is possible using robotic cutting and re-welding methods, but will require considerable mass and complex robotics to maintain the capability. Operating the tubing within the overburden casing will reduce the risk of excessive wear or damage to near zero. General design approaches would specify tubing with extra wall thickness to reduce stress loads. To increase reliability, designers should select tubing material to meet required service and test the tubing with complete non-destructive testing methods using tubing from same production runs with comprehensive destructive testing to assure suitability.

As far as hole stability is concerned, arguments supporting the compatibility of umbilical drilling and overburden casing drilling methods can be applied to coiled tubing drilling as well; however, commercial prototypes are not believed to exist at this time.

Conclusions

Coiled-tubing deployed drilling assemblies should not be eliminated from the final list of drilling technologies.

1) **Spooling energy requirements are not unreasonable for the elastic spooling and plastic spooling examples calculated.**

2) **Reel sizes will fit within the assumed volume constraints.**

3) **The mass of the coiled tubing is not a substantial part of the mass budget, assuming that a diameter to thickness ratio for the coiled tubing of 20 provides an adequate robustness to support shallow drilling.**

4) **Low values of drilling thrust and torque can be applied with the coiled tubing. If high levels of thrust and torque are required, down-hole thrusters and rotary momentum converters can be used to produce percussion and rotary impact**

drilling, and tractors or wall anchors combined with down-hole motors can be used to produce steady-state thrust and torque.

5) **Coiled tubing is highly compatible with casing-advance systems.**

Segmented Drill-stem Conveyance

In this section, we evaluate segmented and coupled drill-stem conveyance methods. This is the most common method of shallow-to-deep drilling in which the drill string conveying the bottom-hole assembly (BHA) is extended from the surface one segment at a time. The entire drill string is normally rotated, and when bits are changed the string segments are raised, uncoupled and stacked one at a time – a very time-consuming process.

Concerns

For drilling in the Martian environment, there is a question of reliability of joints after 200+ runs of drill stem using robotic assemblers (iron roughnecks). Issues include:

1) Structural integrity of joints

2) Pressure integrity of joints (if required)

3) Galling of mechanically connected joints.

4) Cleaning and lubricating mechanical joints before make up.

5) In the dry Martian environment, there is a high potential for electrostatic forces to distribute and adhere fine dust to metal surfaces, and any joint cleaning may introduce undesirable contaminates to the borehole.

6) Method of assembly and disassembly of joints.

7) Method of providing reliable telemetry and other required downhole utilities through coupled joints.

8) Interruption of drilling process each time a joint of drill stem needs to be added.

Segmented threaded and coupled drill stems is the most mature of the drill-stem conveyance methods in terrestrial use. For shallow Martian drilling, load requirements and pressure requirements, if any, for the joints will be low relative to normal deep hole drilling on Earth. However, threaded joints are highly subject to thread damage and galling. This failure mode is reduced or eliminated by one or more of the following:

1) Use of dissimilar metals on contacting surfaces.
2) Proper surface finish or treatment after the threads are cut.
3) Use of thread lubricants.
4) Cleaning the threads before make up.

Cleaning of joints may be difficult in an ultra-dry environment. Wiping methods may be ineffective due to the potential for extreme electrostatic attraction of dust to metal surfaces. Chemical methods to mitigate the problem may introduce contaminates since copious application of thread compound lubricants will likely be needed. In addition, dust may cause corrosion of metal surfaces. Finding a suitable joint compound that is acceptable will be challenging because of the low-temperature, low-pressure, and ultra-dry environment. It will be necessary to eliminate high-vapor-pressure volatile materials that are commonly used, yet viscosity at 200 degrees K must be low, and contamination concerns will eliminate carbon-based materials to the greatest extent possible.

Damaged joints are readily replaced, but mass constraints will severely limit the number of extra joints. Technology for automated assembly and disassembly is in an advanced state. However, automation requires considerable mass to provide the robotics needed. Proper joint design will be needed to assure reasonable power levels to couple and uncouple the joints to proper makeup torque. Selecting a drill-stem joint length that corresponds to the core length to be retrieved can minimize interruption of the drilling process to add a drill-stem segment. Much of the robotics and control equipment that will be required to assemble and disassemble bottom-hole-drilling assemblies, overburden casing (if applicable), and wireline logging tools can be used to run the drill stem. Therefore, the mass impact of segmented drill stem may not be that significant.

Some telemetry support systems for segmented drill stem are currently used or under development and may be adaptable for Martian environment. These methods include acoustic telemetry through the drill-stem wall and joint wall and internal wireline run inside drill stem; the telemetry and power cables are inserted into the bore and connected to the BHA with a "wet connect"-type of connection.

Conclusion

Segmented drill stem should not be eliminated from the final list of drilling technologies.
1) **Special design joints may be needed and several issues will have to be addressed because drilling assemblies will require a suitable joint technology to support change-out of drilling assemblies and core heads.**
2) **Mass of robots to assemble and disassemble the drill stem is not expected to be excessive and may be able to run both the drill stem and the overburden casing by making joint-gripper size readily modifiable.**
3) **Telemetry using an internal umbilical inserted after the drilling assembly is in place on the bottom of the hole will provide reliable telemetry. A dry version of wet connect technology will be required to establish a reliable connection in a cold, dry, and dusty, as opposed to wet, environment.**

Evaluate power transmission methods based on energy/power and mass constraints

Concerns and Analysis

Concerns for power transmission down hole include efficiency, reliability, and mass. The same issues apply to closed-loop hydraulic systems to support thermal management requirements.

For 200-m depth, efficiency will not be a major issue except for open-loop air systems and a closed-loop air system that will have to operate at relatively low pressure to avoid precipitation at 200 degrees K. To keep mass of systems low, closed-loop hydraulic or high-pressure pneumatic systems should complement thermal management systems; the systems should be sealed so that leakage is recovered or eliminated. To keep power losses low, the system should avoid compression and use pumping to boost pressure if possible.

Conclusions
1) **Eliminate open-loop, air-pneumatic downhole motors.**
2) **Add hydraulic and closed-loop, sealed systems that support thermal management and power transport.**

Evaluate overburden hole stabilization or casing advance methods based on energy/power and mass constraints.

<u>*Overburden Casing Advance Systems*</u>

<u>**Concerns and Analysis**</u>

The general concerns about hole stabilization approaches include the complexity of the method of advancing the string, evaluating the required strength of the casing or hole support system, and the procedure that follows when or if the string gets stuck.

We begin our analysis by evaluating dual-string casing advance systems. In this approach, the drilling assembly is advanced inside of a second, concentric tube (casing) that is advanced as the hole is extended and supports the borehole wall.

There are several methods of advancing the casing.

1) Under-ream (actually, over-ream, but the term used in the drilling community is under-ream, so we will use it here) the hole and lower the casing as the under-reamer moves ahead. With this method, one can choose to either under-ream hole simultaneously with coring [56] in soft, unstable formations, or under-ream the hole after each coring run in harder, more stable formations.

2) Drill unconsolidated and soft formations with a drilling guide-shoe and rotate the casing from the surface until torque to rotate the casing exceeds acceptable levels. With this method, slow rotary drive can be developed from the same grippers used to screw casing joints together. Also, some thrust may be needed until casing weight is adequate to advance the casing.

3) Use a surface-powered sonic drill to advance the casing after hole collapse starts to impede casing advance. With this method, it would be desirable to rotate the casing, if possible, and/or assist advance with down-hole impulse loading to pull the bottom of the casing down when necessary

4) Operate the casing advance system at low power levels in slow motion in an attempt to prevent agitation of unstable bore walls.

Next we consider the required strength and mass of the casing string. Standard American Petroleum Institute collapse calculations [57], modified to include properties for aluminum and titanium, produce calculated collapse pressures for thin-wall casing that are much higher than the values expected to be generated in shallow holes. However, thin-wall casing is highly vulnerable to non-uniform loading that is likely to occur in a bore collapse situation and the API calculation has not been validated for non-traditional casing materials (only for low carbon steels). Theoretical point or line loading of the tube indicates that thin-wall tubes will support high loads, but results are not realistic because this is a stability calculation and simple models are not accurate. One way to address the problem is to develop low-mass stiffening technology to achieve thick wall string performance with low-mass wall. Keeping the gap between casing and drilled bore small may reduce the possibility of wedging larger particles from the bore wall in the gap as the casing is advanced.

Regardless of the design, there will still be a significant probability of failure of the support system, so some consideration needs to be given to the procedure when or if the overburden string gets stuck. Several drilling strategies can be suggested to take into account the effects of possible borehole instability:

1) Core ahead to 200 m, or until potential unstable formation is encountered and complete the hole at a depth less than 200 m before the coring assembly gets stuck.

2) Core ahead to 200-m depth or until the coring assembly gets stuck and leave the core assembly on hole bottom but release and retrieve drill stem, if possible. Then, complete hole above the core head.

3) Reduce the size of the coring assembly and run a smaller diameter overburden string inside the original overburden casing. This approach is the traditional method of dealing with complex drilling environments, but it requires considerably more mass for extra drilling assemblies and casing.

Conclusion for overburden casing advance methods

Casing advance systems are the most mature drilling technology for overburden drilling

1) The depth limit is based on an inability to advance casing due to the bore wall collapse that results from thrusting to overcome friction between bore wall and casing.

2) The method is characterized by complicated surface equipment and operations required to support dual string drilling.

3) Down-hole reaming is difficult in hard rock and highly fractured hard rock.

4) There is no fundamental reason to eliminate this technology, but high friction may prove to be a problem despite the hope that low gravity should increase depth capability.

Rock Melting Hole Stabilization

Rock melting is a specialized thermal drilling technology that features inherent hole stabilization in the form of a rock-glass hole lining that is formed as the drill progresses.

Concerns and Analysis

Rock melt drilling hole stabilization is a demonstrated technology for unconsolidated sand on a laboratory and limited field scale, but it has not been demonstrated in frozen soils or permafrost. While the high temperatures are potentially beneficial from the point of controlling biological contamination, there is concern that the heating may cause heaving of frozen soils and make it difficult to avoid overheating scientific samples. From the stability point of view alone, it is possible that the equilibrium diameter of a borehole in ice or permafrost may not be stable after a hot bit passes. There is additional concern that this method may not be suitable for drilling hydrates and may destabilize surrounding ground ice. Nevertheless, rock melt stabilization might be a good approach for portions of a drill hole, for example, forming a surface casing in highly unstable, near-surface zones.

Conclusions for Rock Melting Stabilization

Rock melting drill liners produce stable well bores in unconsolidated sands and fractured rock but may not be suitable for drilling hydrates and ice. High temperatures may cause heaving and collapse of frozen soils and permafrost.

Down-hole Fabrication of Overburden Casing

One possible way of overcoming the problems of advancing overburden casing from the surface is to fabricate a casing down hole as the drilling progresses.

Concerns and Analysis

A down-hole-fabricated casing does not have to move, so hole collapse has no detrimental effects unless collapse occurs in or below the region of the fabrication process, or collapse deforms the overburden casing to interfere with operation inside the casing. A commercial technology of this type does not presently exist. Concepts have been proposed by the oil companies [58, 59] and the oil service industry, but no evidence of working prototypes has been offered. One problem with the methods that are being developed is that oil field technology may support fabrication in a deep drilling, mud-filled hole, but may be unsuitable for the Martian environment.

Several casing fabrication methods that have been proposed for application in the trenchless utility industry were investigated. These include casing fabricated from a thin strip that is transported down the hole and welded or zipper-hooked into a spiral wound casing. Another version of this approach is expanded casing fabricated from thin tubes that are hydraulically or mechanically expanded to fit in the under-reamed hole and sealed to previously-installed casing joints. Commercial products are presently available that expand liners to reduce the hole size reduction required [60], but expansions to eliminate hole size reductions will require customized liner materials to achieve the high elongations required.

A different approach to down-hole fabrication of casing is low temperature bore-wall stabilization technology. In this method, down-hole injections of material are used to stabilize unconsolidated or poorly consolidated material and strengthen it to be self-supporting. A fundamental issue with this method is whether to transport imported material or use a natural source of material. No natural material except for CO_2 has been identified. However, the operating temperature may be too close to the triple point of CO_2 to use dry ice as a stabilizing material. The possibility of using imported water deserves some study to see if transported mass would be equivalent or less than the mass of metal overburden casing on a worst case scenario. The freezing of terrestrial moisture in damp formations has been demonstrated [12, 61] to stabilize unconsolidated material. Phase stability will be an issue in the Martian environment.

A variation of this method is some form of cementing technology. Potential 200 K cementing materials would have to be identified. Terrestrial experience suggests that injection of cement into porous and fractured materials would be difficult to control. Possible methods of placement would be injection or spraying technology. Differential wetting properties may cause some fractures or porosity to take-up too much material and leave other fractures or porosity untreated due to poor wetting or differing capillary pressure effects. Another potential problem is that loss of materiel into the well bore can stick the placement assembly and waste materials. Another variant of this method is melting or chemical modification of a solid, flexible well lining material to be absorbed into exposed porosity and fractures. This method of well bore stabilization represents a good research area since no commercial processes were identified.

Conclusions for Down-hole Fabrication of Overburden Casing

Down-hole fabrication of casing and in situ bore-wall stabilization are attractive concepts, but no prototype systems or experimental data have been identified to support their use. Prototype design and experimental demonstrations are needed to evaluate these methods.

Underground Mole Technology

Underground moles are tetherless, self-contained or umbilical-powered soil penetration devices that allow the hole to collapse behind the body of the device. Hence, hole stability is not

normally an issue in their use. Moles advance by auger displacement of unconsolidated soils or by some form of percussion or rotary-percussion comminution.

Concerns and Analysis

Moles are particularly well adapted to unconsolidated, porous soils where there is little net volume change in the material as a result of its passage. In hard rock however, the cuttings must be reconsolidated and packed into the region behind; this is likely to require very high energy. There is normally no provision for core or samples in vertical drilling with moles. Instead, the device has to drill itself back to surface to return samples. For our application, there is the additional problem that drilling rate will have to be extremely slow in hard rock to preclude over heating of the mole (assumes heat rejection to the drilled formation).

Moles that use some form of umbilical connection to the surface have several deployment methods and associated issues. Surface deployment requires a tether to move relative to repacked materials, and frictional resistance will limit depth of penetration. Down-hole deployment requires a large mole to store umbilical and has severe depth limitations if umbilical is sized to transport cuttings and/or core transport. Design of an umbilical to support power, cuttings, core, and heat rejection transport turns the umbilical into a large diameter tube that looks more like overburden drilling than a mole. Another problem is that consolidating the non-transported cuttings may collapse the umbilical.

Mole technology has been demonstrated in unconsolidated material and soft materials, but a hard-rock demonstration was not identified. There is very limited depth capability unless the umbilical is large enough to retrieve cores to the surface and send down materials to fabricate the umbilical down hole. In that case, the system begins to look more like one of the overburden casing systems proposed above and less like a mole.

Conclusions for Underground Moles

Moles are attractive concepts, but are not suitable for hard-rock drilling short of the development of revolutionary comminution and re-consolidation technology.

Summary of Mechanical Drilling Systems Remaining on the Final List

Short list technologies

Comminution
- ♦ *Mechanical rotary, percussion and combined drills - NOT REMOVED*
- ♦ *Melting drills – short list drilling method 5A, 5B, and 5C REMOVED due to high power requirements combined with high heat rejection load (see thermal management) which can not be simultaneously supported.*

Drill conveyance
- ♦ *Hollow stem auger sections - NOT REMOVED*
- ♦ *Segmented drill stem and segmented casing - NOT REMOVED*
- ♦ *Reeled continuous tubing - NOT REMOVED*
- ♦ *Umbilical wireline/sand line - NOT REMOVED*

Drill-cuttings transport
- ♦ *Auger – short list drilling method 1 REMOVED due to depth limitation on cuttings lift based on terrestrial experience and model results.*

- ♦ *Pneumatic slurry – short list drilling methods 2A, 2B, 2C, 3A, 3D, 4A and 4B REMOVED –due to excessive power requirements and loss of returns.*
- ♦ *Continuous core - NOT REMOVED*
- ♦ *Scow bailer or bucket auger - NOT REMOVED*
- ♦ *Repacked holes – short list drilling methods 5A REMOVED – due to inability of umbilical moles to consolidate cuttings and repack hole in hard rock.*
- ♦ *Pulsed air flow - ADDED*
- ♦ *Acoustic agitation - ADDED*

Well stabilization

- ♦ *Dual string casing while drilling or coring - NOT REMOVED*
- ♦ *Densified and annealed glass bore lining - 6A, 6B, and 6C REMOVED – due to insufficient power availability.*
- ♦ *Repacked holes – short list drilling methods 5A REMOVED – due to inability of umbilical moles to consolidate cuttings and repack hole in hard rock.*
- ♦ *Downhole bore-wall stabilization - ADDED*
- ♦ *Downhole casing fabrication - ADDED*

Power transmission

- ♦ *Mechanical rotary and/or reciprocation - NOT REMOVED*
- ♦ *Electrical - NOT REMOVED*
- ♦ *Pneumatic – open-loop air systems REMOVED due to high circulation pressure and power losses – closed loop high-pressure air systems NOT REMOVED*

Thermal management

- ♦ *Passive cooling (drill bit-to-formation, cuttings, and core) - NOT REMOVED*
- ♦ *Open-loop air cooling and air circulation and expansion - short list drilling methods 2A, 2B, 2C, 3A, 3D, 4A, 4B, 6A, 6B REMOVED due to high circulation pressures and power requirements, precipitation and plugging problems.*
- ♦ *Water circulation – 6C REMOVED - due to freezing and plugging problems.*
- ♦ *Closed-loop non-air circulation and refrigeration systems - ADDED*

Remaining short list drilling systems

> *3B Sonic drill (for casing advance system)*
> *3C Ultrasonic drill corer (assuming fluidless cuttings removal is possible)*
> *4C Percussion churn air drilling (assumes dry drilling with serious hole-cleaning issues to be resolved)*

The net result is that all demonstrated terrestrial systems have been removed, but individual subsystems remain to be assembled into custom Mars drilling systems.

Remaining subsystems.

Comminution

- • *Mechanical rotary, percussion and combined drills*

Note that rotary drilling systems where kicked off the list for non-comminution issues, but should be considered in subsystems considered for the example systems.

Drill conveyance

- *Segmented drill-stem, reeled tubing, and umbilical*

Drill-cuttings transport

- *Bucket auger, continuous core, pulsed airflow, and acoustic agitation*

Pulsed air flow and acoustic agitation have been added to provide bit cutter cleaning to prevent excessive regrinding and cutter wear where conventional continuous air flow would suffice in terrestrial drilling.

Well stabilization

- *Overburden casing advance systems, down-hole bore-wall stabilization, and down-hole casing fabrication*

Down-hole bore-wall stabilization and down-hole casing fabrication have been added as research alternatives to conventional overburden drilling methods that tend to be operationally complex and depth-limited in terrestrial drilling.

Power transmission

- *Mechanical rotary and/or reciprocation, electrical, closed-loop pneumatic and closed-loop hydraulic.*

Thermal management

- *Passive cooling, closed loop hydraulic and high-pressure pneumatic (not air) circulation, and refrigeration cycles.*

Example Systems for Prototype Demonstrations

As discussed in the section on **Analysis Approach**, we are left with a list of credible subsystems from which a number of custom drilling systems can be assembled that we believe could meet the Mars shallow drilling mission requirements and constraints. No decisions can be made at this time as to which of these systems might be optimum because there is insufficient data on which to base comparisons. However, it is instructive to look at several of these possible systems as examples of how the subsystems can be combined.
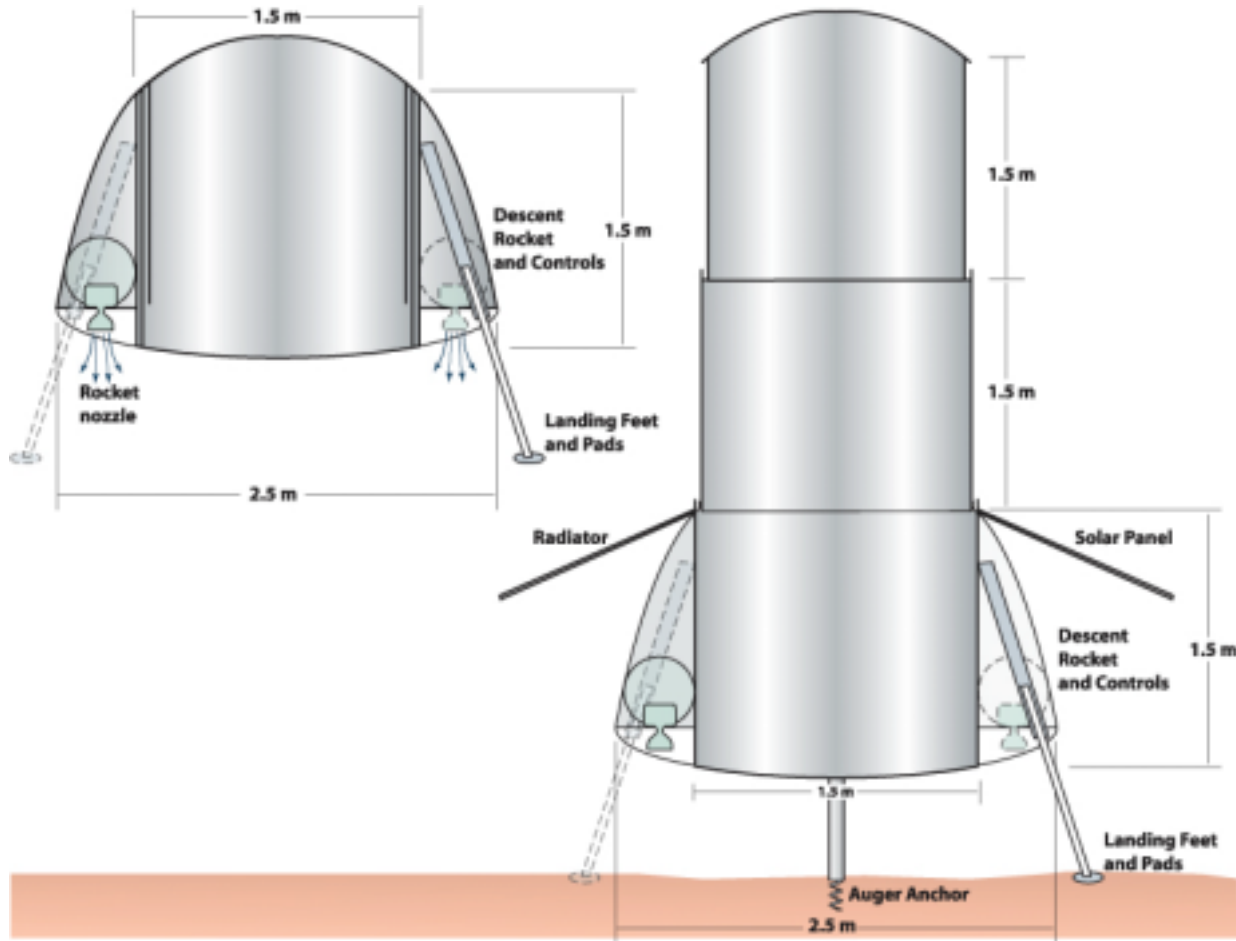
Figure 17. Landing configuration and deployed envelope of the example systems.

A notional concept for the landed envelope for all of the example systems is shown in Figure 17. The main point of this figure is the idea that, since most drilling systems tend to be tall, some post-landing erection and deployment will be necessary, including anchoring and leveling. The figure also shows the basic dimensions we have assumed for all of the systems.

System 1 – Coiled-Tubing-Deployed, Hydraulic-Motor-Powered, Refrigeration-Cycle-Cooled, Rotary Diamond Core Drill and PDC Reamer, with a Down-hole-Fabricated Hole Stabilization Liner, (Figures 18 and 19).

System 1 Description

Comminution - Rotary-ultrasonic diamond core drill and mechanical rotary PDC reamer run sequentially.

Drill system conveyance - Reeled tubing for continuous coring, under-reaming, bucket auger deployment, and down-hole-fabricated liner placement.

Drill-cuttings transport - **Continuous core, pulsed airflow and acoustic agitation transport of core-head-kerf cuttings to junk basket and bucket auger run following reaming.**

Well stabilization – **Down-hole expanded-metal-liner fabrication and placement simultaneous with under-reaming.**

Power transmission - **Closed-loop hydraulic circulation.**

Thermal management – **Passive cooling, closed-loop refrigeration cycle.**

Down-hole Telemetry – **Hardwire, aluminum and fiber optic cables, installed inside coiled-tubing drill-stem.**

Potential System Synergies

1) **Hydraulic-motor power for coring, reaming and liner expansion, and auger rotation.**
2) **Closed-loop hydraulic fluid circulation for power transport and thermal management.**
3) **Closed-loop circulation and internal hydraulic tubes installed inside a coiled-tubing drill stem.**
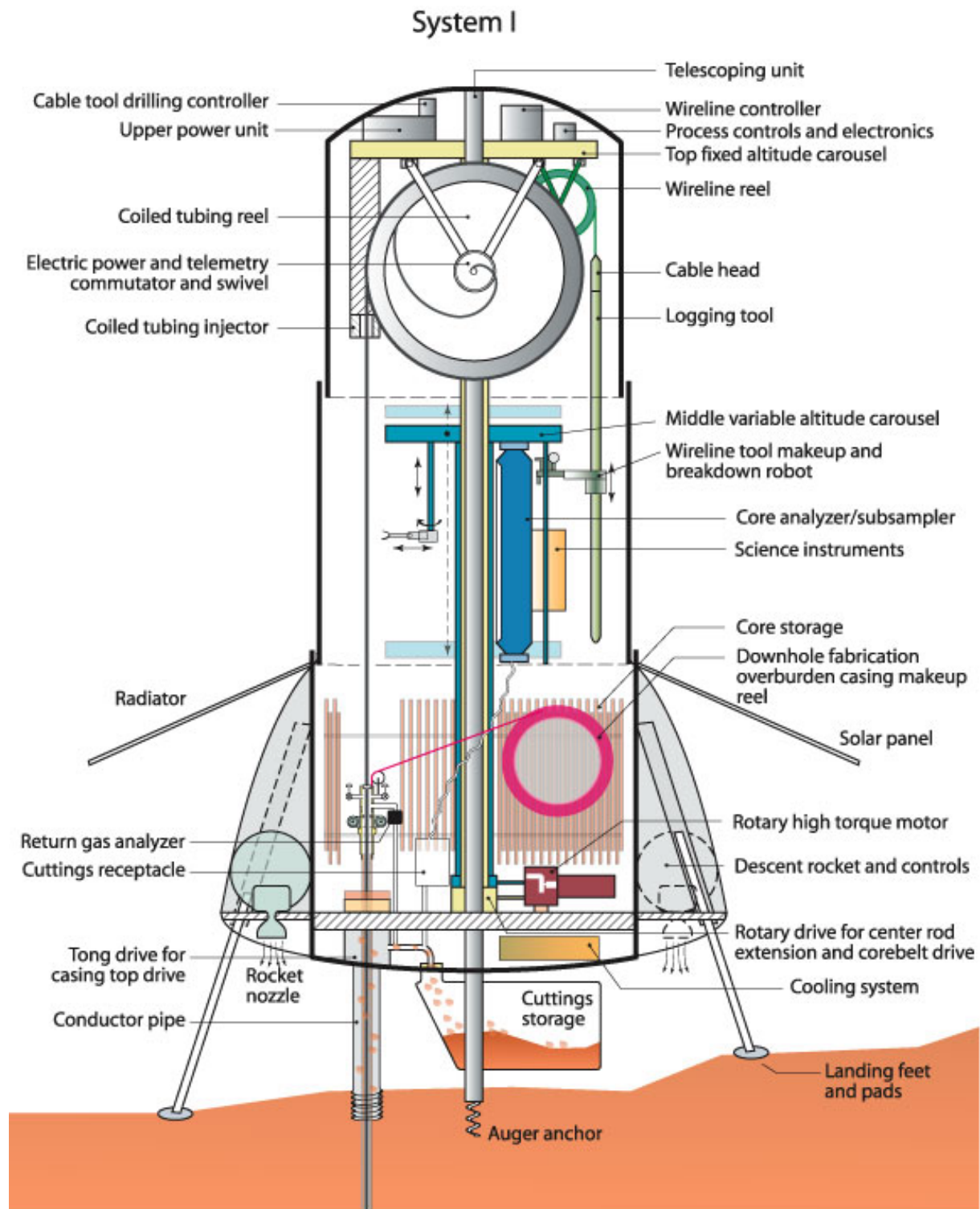
Figure 18. Conceptual layout of Example System 1
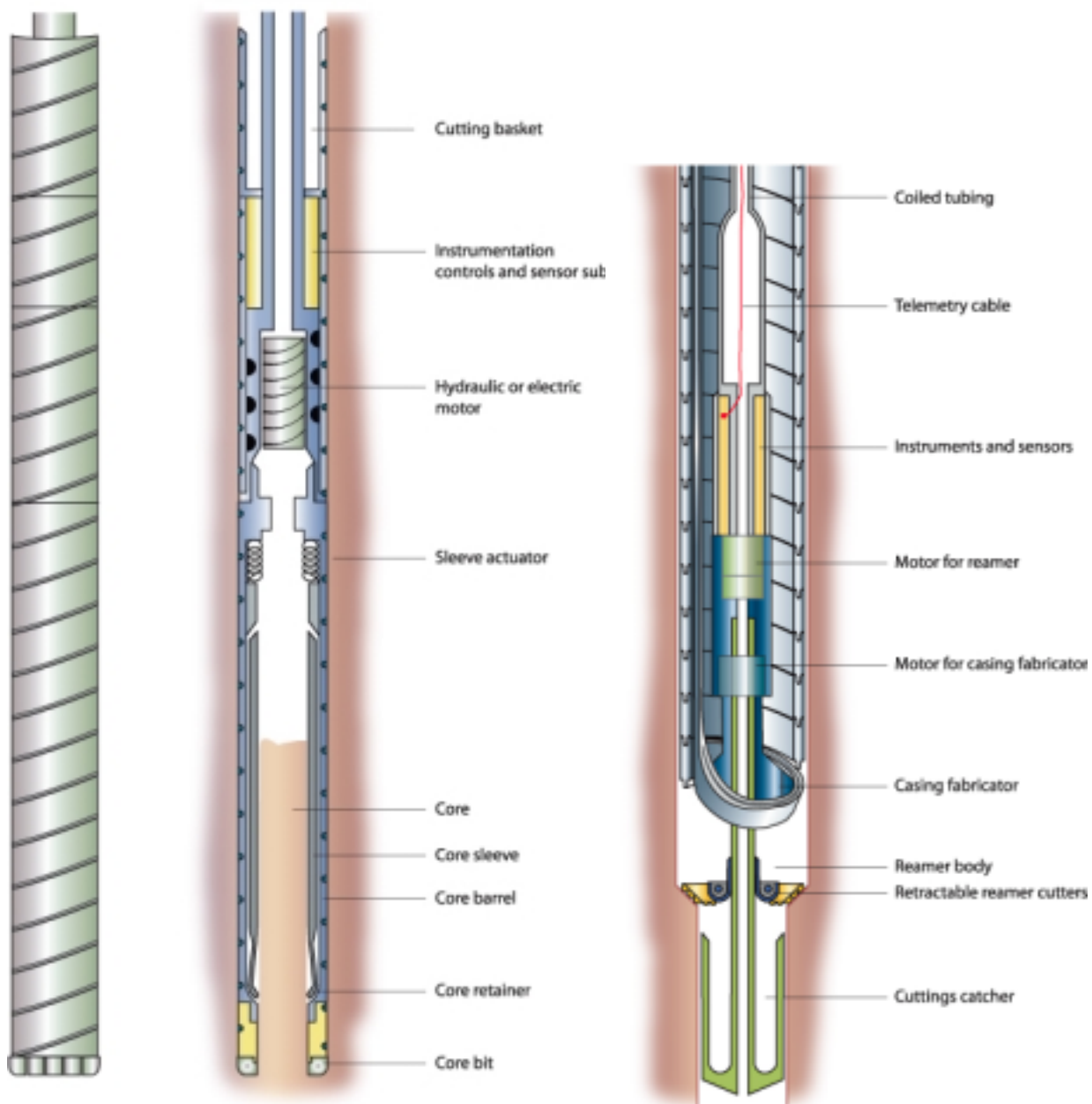
Figure 19. Bottom-hole Systems for System 1

Left.   **Coring Assembly. Rotary-ultrasonic diamond core drill with an instrument and sensor sub and cuttings basket on top. External view on left and internal view shown on right.**

Right. **Reaming and Hole Stabilization Assembly. Mechanical rotary PDC reamer with a cuttings basket below the reamer and a conceptual down-hole casing fabricator operating just above the reaming assembly. This assembly is run sequentially with the coring assembly and may require several runs to remove cuttings.**

System 2 *– Umbilical Wireline-Deployed, Surface Reciprocation-Powered, In Situ Dissipation-Cooled, Percussion (Cable Tool) Sonic Core Drill and a Down-Hole, Bore-Wall Stabilization System, Figures 20 and 21.*

System 2 Description

Comminution - **Cable tool percussion core drill with superimposed acoustic reciprocation to provide indexing (movement of cutters relative to rock so that percussive blows hit less damaged rock each stroke) and cuttings cleaning and initial bottom-hole clearing.**

Drill systems conveyance - **Umbilical wireline.**

Drill-cuttings transport - **Continuous core, down-hole-generated air blast and acoustic agitation to clean core bit during indexing, and wireline-deployed bucket auger between bit runs.**

Well stabilization - **Down-hole, bore-wall stabilization using wireline-deployed injection and casting tool. Injects a liquid or slurry, manufactured from fine cuttings, into porosity and fractures that then freezes or dries (hydrates) to form a formation binder (liquid and slurry chemistry do not presently exist for 200 degree K or for powdered basalt or clastics)**

Power transmission - **mechanical reciprocation for main drilling and electrical for acoustic source and bucket auger.**

Thermal management - **passive cooling to cuttings, core and cable and bottom-hole air circulation circuit.**

Downhole Telemetry – **Hardwire, aluminum and fiber optic cables embedded in umbilical wireline.**

Potential System Synergies -**Reciprocation of wireline to power the main percussive cycle and simultaneously power a single-cylinder, positive-displacement compressor to circulate air around the BHA in support of cutting transport (air puff) and bottom-hole-region thermal management.**

Acoustic bit indexing and acoustic reciprocation-induced cuttings transport.

Down-hole air circulation for both cuttings lift to a down-hole storage receptacle (cuttings basket) and bottom-hole-region thermal management.
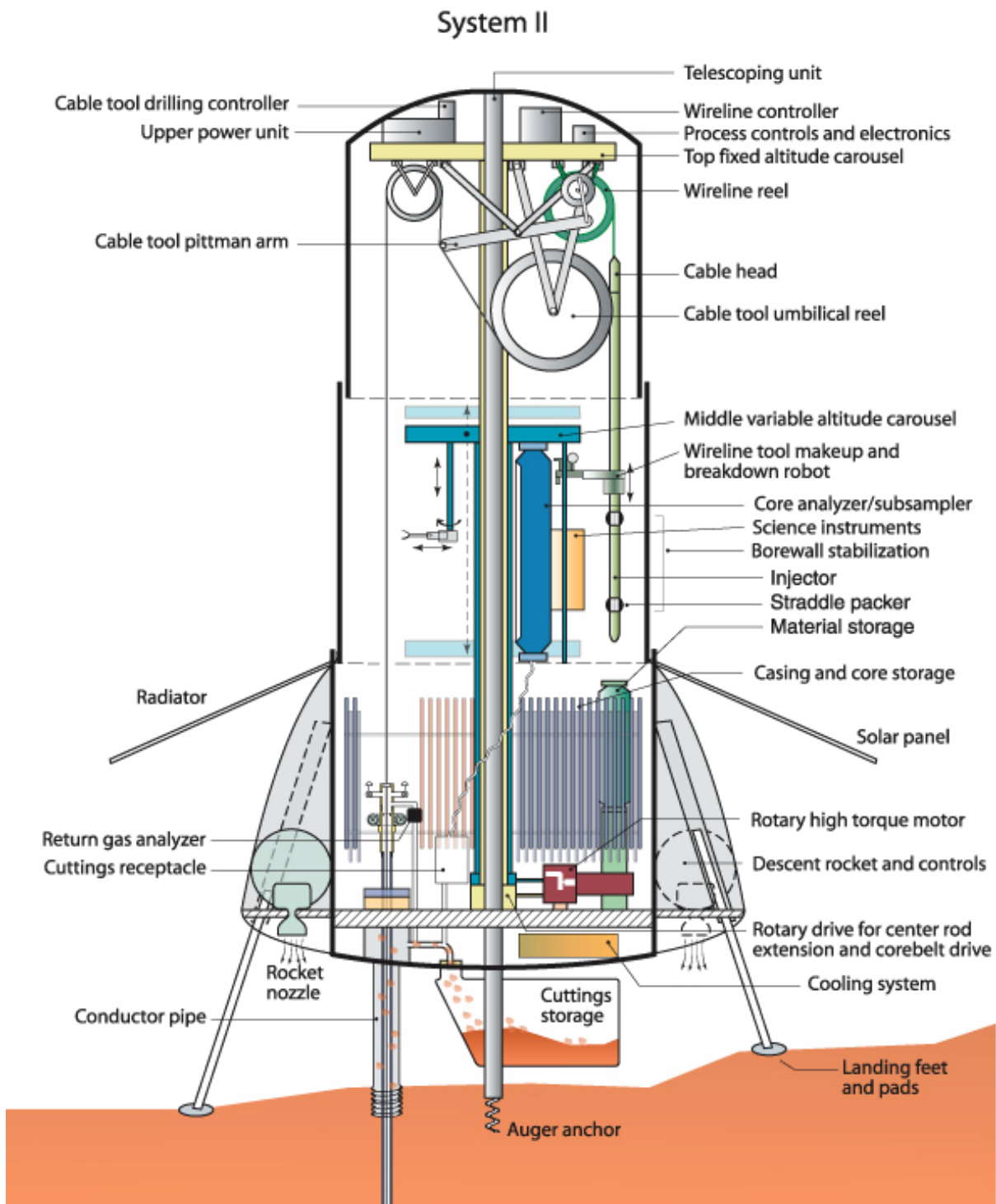
Figure 20. Conceptual layout of Example System II.
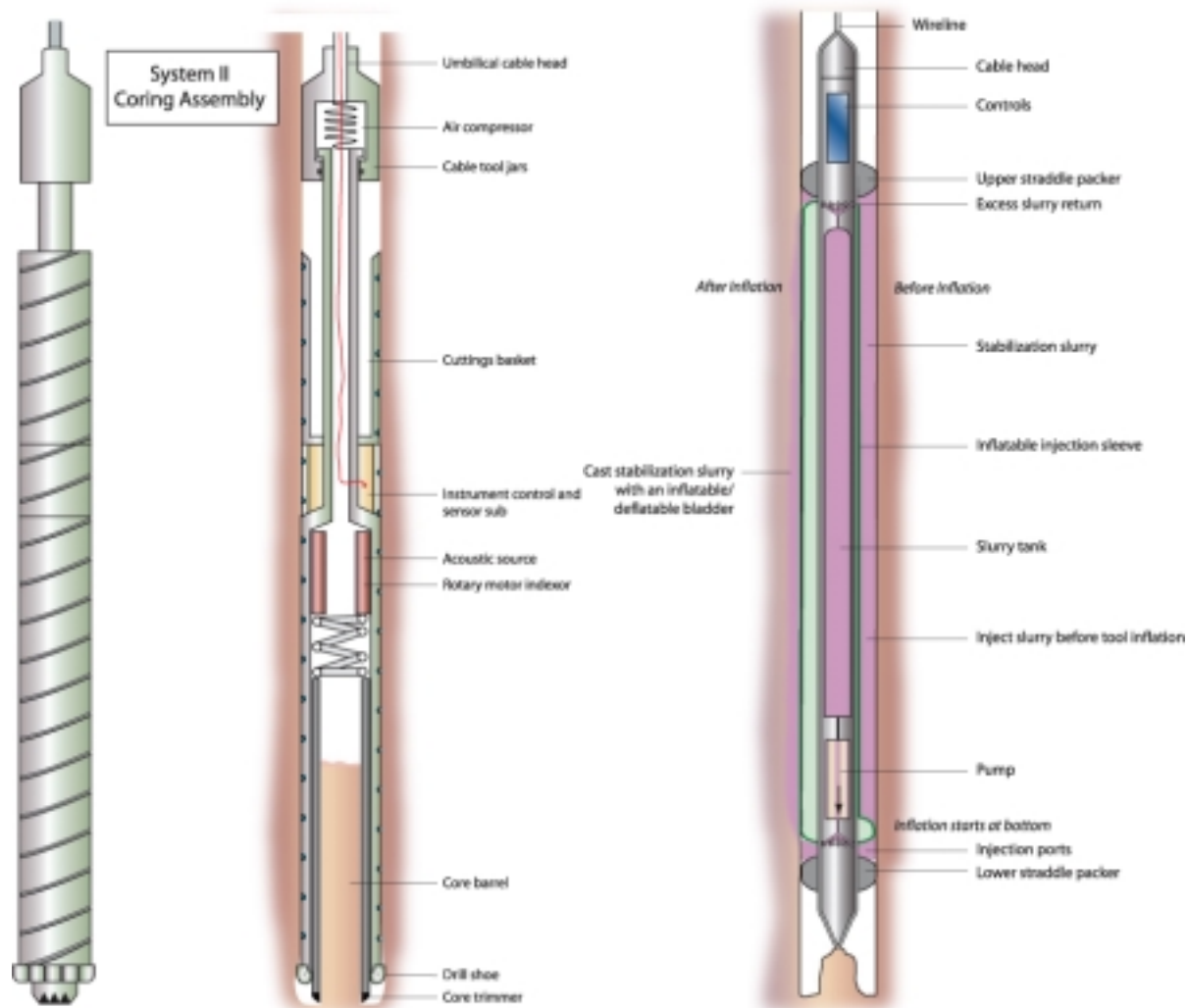
Figure 21. Bottom-hole Systems for System 2

Left. **Coring Assembly. Cable tool coring drill with an electric powered sonic overprint for indexing and power input to spiral flutes cuttings transport system, an instrument and sensor sub, a cuttings basket, and an air puff compressor combined with cable tool bumper jars on top. External view on left and internal view shown on right.**

Right. **Hole Stabilization Tool. An umbilical deployed straddle packer tool (1) isolates sections of the hole for a stabilization grout, (2) injects a, presently unidentified, liquid slurry or paste through ports in the tool just above the bottom packer, (3) fills a thin annular gap up to the top packer, (4) displaces the slurry by expanding a long packer element in the annulus (from the bottom upward) out to the formation, (5) displaces fluid into the formation or into ports just below the top packer by taking the path of least resistance, and (6) casts the slurry in the formation to stabilize the bore. The packers are deflated and tool is then removed with any excess slurry recovered for recycling. This assembly is run sequentially with the coring assembly.**

System 3 *– Segmented Drill-stem-Deployed, Electric Motor -Powered Top Drive Drill-stem Rotation, Refrigeration Circulation System for Cooled Drilling Assembly, Rotary Core Bit, with a Dual-String, Rotary-Overburden-Casing-Bore-Stabilization System, (Figures 22 and 23).*

System 3 Description

<u>**Comminution**</u> **- Micro PDC rotary kerf drill with auger flutes for cuttings transport and pulsed air flow at bit.**

<u>**Drill conveyance**</u> **– Dual-string, segmented drill stem and casing, and umbilical telemetry and tubes for, high-pressure, low-flow gas for pulsed cuttings flow and refrigeration circuit.**

<u>**Drill-cuttings transport**</u> **- Pulsed airflow, acoustic reciprocation and rotary auger flutes to cuttings receptacle (basket) at top of drilling assembly. Bucket auger-deployed on the rotary drill stem between core runs.**

<u>**Well stabilization -**</u> **Overburden casing-advance systems with rotary reamer shoe on the bottom of the casing.**

<u>**Power transmission**</u> **- Mechanical rotary for overburden casing and down-hole electric motor for core bit.**

<u>**Thermal management**</u> **- Closed-loop refrigeration circuit sealed in the umbilical run inside of the drill stem after each deployment to the bottom of the hole and after each connection to add a joint of drill stem (pull a core or change a bit).**

<u>**Down-hole Telemetry**</u> **– Hardwire, aluminum and fiber optic cables embedded in umbilical that is run after drill-stem deployment and connected to drilling assembly with dry version of "wet connect" technology.**

<u>**Potential System Synergies**</u> **- Air puff circulation through a refrigeration cycle evaporator in the bottom of drill stem to cool the coring system.**
Segmented-tube handling and rotation equipment for both the primary drill stem and the overburden stabilization casing.
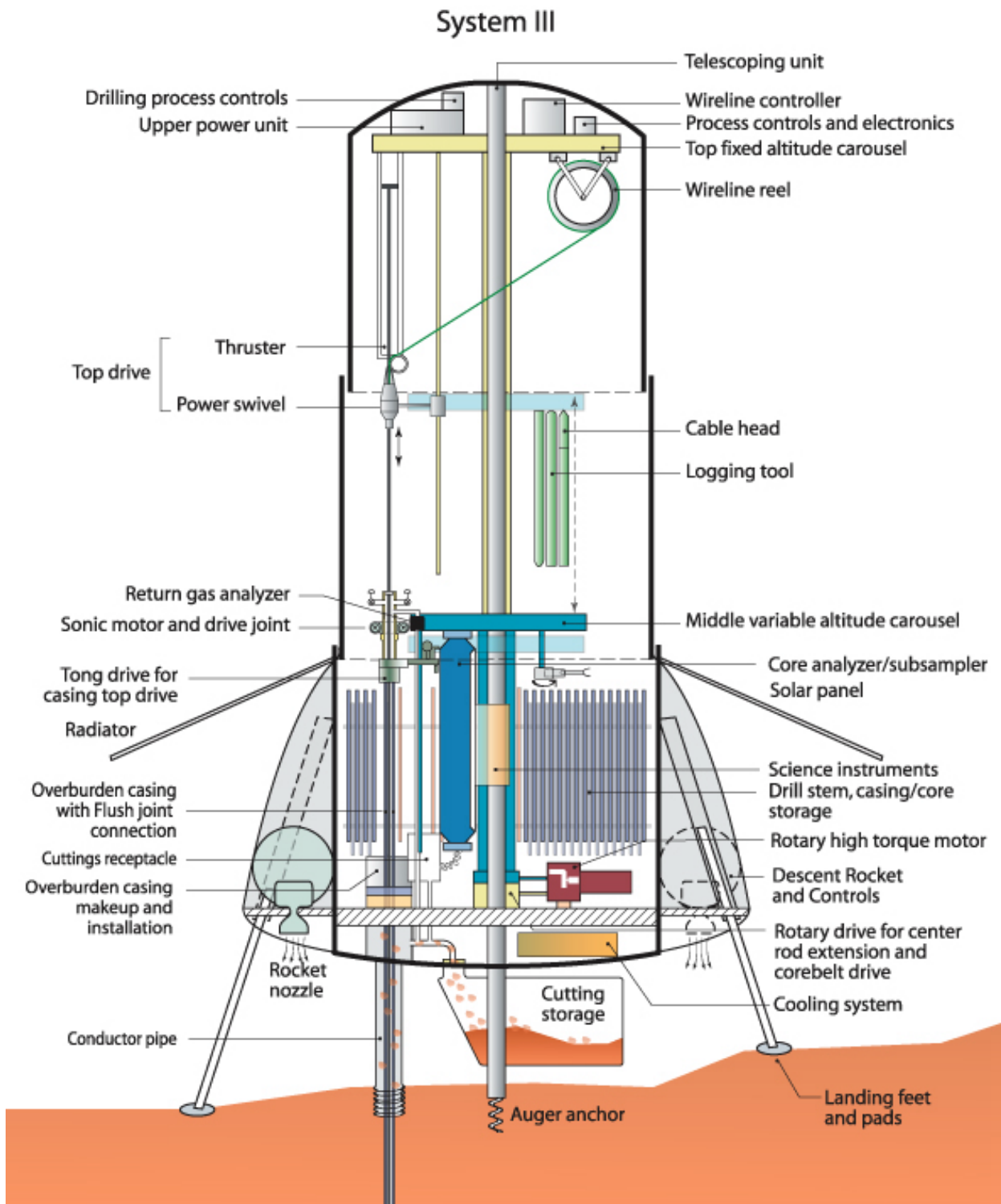
Figure 22. Conceptual layout of Example System III.

T&C drill stem

Overburden casing

Casing shoe – slow rotating
percussion reamer drill

Cuttings basket

"Wet Connect"
telemetry connection

Instrumentation and
sensor sub

Sleeve activator

Core sleeve

Core barrel

Core bit
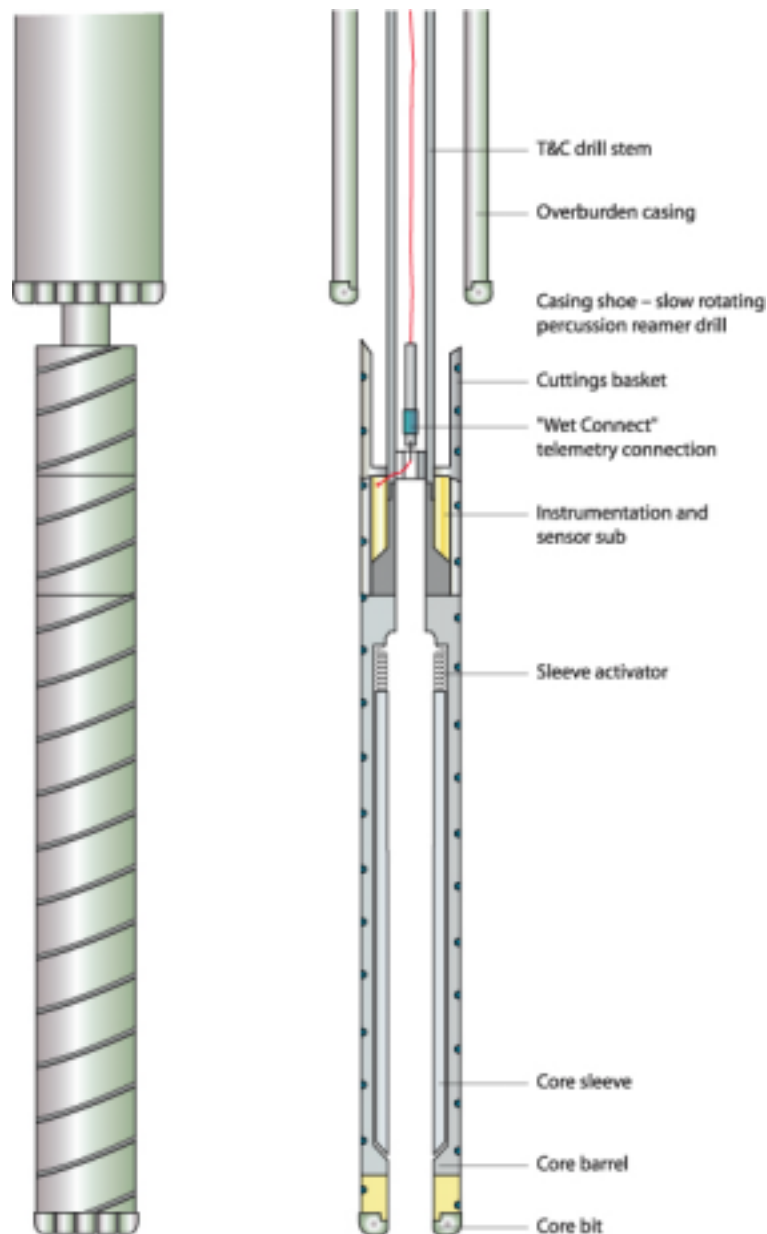
Figure 23. Bottom-hole Systems for System 3. External view on left and internal view shown on right.

Bottom. **Coring Assembly. Micro PDC rotary kerf drill with auger flutes for cuttings transport and pulsed airflow at bit.**

Top. **Reaming and Dual Wall Casing Advance System. Overburden casing-advance system with rotary reamer shoe on the bottom of the casing. Segmented, overburden casing is assembled, inserted and advanced, and rotated with a top drive, dual rotary system.**

List of Critical Subsystems

- **Comminution**
- **Drill Conveyance (Drill Stem**
- **Power Transport and Bottom-hole Conversion**
- **Thermal Management**
- **Cuttings Transport**
- **Automated Drill Process Control**
- **Sampling**
- **Hole Stabilization**

List of Elements Common to All Subsystems

- **Sensors**
- **Process Control**
- **Materials**

Mass Estimates for An Example 200-m Drilling System

[Refer to associated systemmass.xls spread sheet]

The spread sheet contains mass estimates of a set of subsystems that might be included in a low-mass, low-power 200-m drill. The primary drilling system consists of a rotary diamond core drill deployed on continuous coiled tubing. This drill is the minimum size that will allow the extraction of a ~15-mm-core sample. This sample could then be peeled down to an (hopefully) uncontaminated 10-mm-core for analysis. Results are tabulated for various kerf thicknesses, and the resulting well stabilization subsystem. Well stabilization is accomplished with an overburden casing advance system, which naturally gets more massive as the main drill-hole size grows. The lander surface systems include carousels and support masts to handle the coiled tubing unit and subsystems. The carousels are simple wheels with spokes sized to support the subsystem components. The bottom support platform includes two beams sized to support a 445 kN load which might be needed to extract a stuck BHA. The lander legs were not included in this analysis. The radiator was sized for an ethanol cooling system operating at night between 170 and 190 K. The radiator for a refrigeration system operating at night will be somewhat smaller, and could be operated during the day if its edge were kept pointed toward the sun – but at a somewhat larger mass.

Conclusions

The primary conclusion of this conceptual systems analysis of 200-m-depth Mars drilling is that, given the presently agreed upon mass and power limits, only high efficiency, mechanical, overburden-type-drilling approaches are feasible.
Other drilling approaches that we eliminated in the analysis, such as thermal drilling, will have to be reconsidered if mass and power constraints are relaxed.
Drilling performance data for various mechanical drilling methods under realistic conditions does not exist and will have to be obtained in a special laboratory drilling test apparatus. Drill-cuttings management may pose the most difficult issue for mechanical drilling and breakthrough technology development may be needed to solve the problem. This needs to

be determined soon because the solution may take time. Parallel evaluation of possible solutions needs to be funded.

The hole stability environment may be the biggest uncertainty for the drilling system optimization process. Early and extensive evaluation of possibilities is needed to make a best guess of the potential magnitude of the problem or if it is a non-problem. Support for development of downhole stabilization methods (bottom-hole casing fabrication and bore-wall stabilization) should be supported early-on and until the scope of the problem is determined. New experimental facilities may be required to study the problem. Hole stability technology will be the most difficult to evaluate in a simulated terrestrial Martian environment. A special drilling test facility may be required. Special artificial soils and rock samples may have to be developed.

Early efforts to simulate remote/automated control in a communication time-delayed mode will help determine the magnitude of this potential problem and identify the need for down-hole sensors, new or modified control methods, and software development.

Recommendations

Priority List of Subsystems Research Topics

1) *Investigate critical subsystems that require early and extensive laboratory-scale testing. These include comminution, cuttings transport, drilling process automation and robotics, and sample handling.*

2) *Conduct extensive testing in a 600 Pa, 200 degree K, and CO_2-filled chamber.*

   a) *Perform mechanical drilling demonstrations:*
      i) *Rotary, percussive, and combined methods at various percussive frequencies, rotary speeds and thrust levels*
      ii) *Large variety of rocks and formations*
      iii) *Collect extensive data to model bit performance and optimize cutting performance over a wide variety of operating conditions.*

   b) *Investigate bit cleaning and cuttings transport*

   c) *Investigate bit cooling and core heat-up*

   d) *Perform rock strength and coefficient of friction measurements for sample drill system materials and special, extra-dehydrated rock samples (Martian simulants).*

3) *Perform demonstrations of example systems in the laboratory and in the field.*

   a) *Develop a test bed for developing sensors, telemetry and control systems*

   b) *Demonstrate remote-controlled and automatic-controlled drilling in Mars-like drilling environments with various drilling systems.*

   c) *Use appropriate time-delayed communication for remote control.*

   d) *Test various control methodologies under realistic simulations of Martian conditions.*

   e) *Develop test bed for evaluating and determining the best technical approach for bore-wall stabilization.*

4) *Investigate total system thermal management.*

5) *Investigate methods for prevention of contamination of core and samples.*

6) Determine the learning curve for developing test plans and procedures for testing second generation, optimized systems based on results from laboratory investigations and field demonstrations.

Discussion

Research and development is needed on all of the subsystems and elements we have identified
. However in our judgement, some critical subsystems are more important than others are. This is either because of a lack of fundamental knowledge of the physics of the processes on which they are based or a combination of the critical path nature of their function and the unique environment in which they must operate. Among these in priority order are 1) comminution, 2) cuttings transport and disposal, 3) drilling automation and robotics 4) hole support and 5) materials applicability.

Comminution

Although our knowledge of Martian geology is likely to increase rapidly over the next several years, we can presently put very little constraint on the types of rocks that will be encountered in the subsurface. The ranges of properties that are important for drill system assessment are very wide. This problem is compounded by the fact that almost no data are available on key rock properties such as strength, cohesion and coefficient of friction under the low temperature and near-vacuum conditions on Mars. There is reason to believe that strength of silicate rocks may be higher on Mars than equivalent materials on Earth.

The reasoning goes as follows. It is well known (e.g., [62, 63]) that the brittle and ductile strengths of silicate glasses and minerals are strongly affected by the presence of water. This is a micro-chemical-mechanical phenomenon that involves the hydrolyzation and consequent weakening of silicon-oxygen or silicon-metal bonds in the structure. In the brittle field, hydrolyzation of bonds at microcrack tips greatly reduces the stress required to propagate the cracks, thereby lowering the tensile strength and fracture toughness. So, in the absence of water, silicates are much stronger. This "anhydrous strengthening" effect is likely to be particularly important on the Moon, the driest environment known, but may also affect the strength and drillability of rock on Mars. The immobilization of water at the low temperatures and low vapor pressure of water on the Martian surface and shallow subsurface may preclude water diffusion to newly formed crack tips; such water diffusion is necessary for low-stress fracture formation and propagation. The problem is we don't know if Martian conditions strongly affect drillability by this or other mechanisms, and we must know if we are to accurately assess drilling approaches and design optimum systems.

Therefore, our highest priority recommendation is to establish a program of research to obtain data on the comminution of a variety of rocks under carefully controlled conditions of temperature and atmospheric pressure/composition that simulate Martian conditions. This research should begin at the laboratory bench-scale and proceed to larger-scale simulator and field experiments. Careful measurement of a full range of drilling parameters such as WOB, torque, rotation speed, bit and material temperatures and others should be performed. With these data in hand, it will be possible to objectively compare drilling approaches (something we were not able to do satisfactorily in this study), validate models and effectively optimize designs. Without this fundamental data system design will be a laborious process of cut and try engineering that will result in non-optimum, riskier solutions.

Cuttings Transport and Disposal

Only slightly lower on our list of recommendations is engineering research on cuttings transport and disposal under simulated Martian conditions. All drilling approaches require removal of material from the penetration face and transport to somewhere else, usually the surface, to form the volume of the borehole. For mechanical drilling approaches, the comminution process produces rock and mineral fragments of various sizes called cuttings. These cuttings must be removed or else increasing amounts of energy are expended in regrinding them, frictional heat builds up and the drilling process ultimately stops. In terrestrial drilling, water, water- or oil-based drilling muds, or in some cases, foam or compressed air are used to convey cuttings, simultaneously cooling the bit and down-hole assembly.

Under the constraints of this mission study, we have calculated that it is not possible to convey even fine-grained cuttings (0.1-mm diameter) using low-pressure-drop, continuous flow of compressed Martian atmosphere; transport of the coarser cuttings produced by some low-energy comminution methods appears even more problematic. On the other hand, analysis has led us to believe that some combination of (ultra)sonic vibration, auger ramping and dynamic gas flow (puff) will be effective in conveying cuttings, probably by short-distance conveyance into a cuttings transport basket (similar to a conventional bottom-hole junk basket) that is then removed to the surface as part of the drilling assembly when core is pulled or a bit is replaced. However, this has not been demonstrated, and certainly not under Martian conditions. We emphasize that data from experiments for terrestrial applications cannot automatically be used to assess processes under Martian conditions. For example, it is not clear whether conveyance of fine drill cuttings in terrestrial experiments on (ultra)sonic drilling is due to particle contact momentum exchange or vibratory motion of the fluid (water or air) that is always present in these experiments. In the near vacuum conditions of Mars, (ultra)sonic conveyance of cuttings may not be as effective as it is under Earth conditions with much higher density fluids present. This needs to be ascertained with experiments that simulate Martian conditions.

Therefore, our recommendation is to perform experimental research on cuttings removal and transport approaches under simulated Martian conditions of temperature and atmospheric pressure/composition. In many instances, these experiments could be performed in conjunction with the comminution experiments recommended above and, in all cases, using the same experiment facility and environmental simulators needed for comminution testing.

Drilling Automation and Robotics

Some of the important issues that we were barely able to address in this study were the requirements, state of technology and applicability of drilling/sampling automation and robotics. Terrestrial experience has demonstrated that drilling is a natural (planetary) environment-driven process, and therefore, complex and unpredictable – a situation that does not lend itself well to autonomy. For this reason and because of the inherent difficulty of installing and operating down-hole process sensors (that will not be destroyed with the rock breaking process), automation has been slow to penetrate the drilling industry, and what has been accomplished in recent years is often closely held for competitive advantage. However, it is clear that drilling on Mars will require automation to a degree never achieved in terrestrial practice. The achievement of robotic drilling will require a very dense, real-time measurement of the drilling process. Sensing of a few parameters at the surface, typical of terrestrial drilling, is unlikely to work. Instead, extensive down-hole sensing of the drilling process, telemetered to a surface computer running comprehensive process control software will be needed but does not presently exist. Since little experience is available in this area [64], it is imperative that a research program on

drilling automation be initiated as soon as possible. In order to define the issues that will need to be addressed, early deployment of several different field-scale rigs is proposed. Each rig would support a different mechanical drilling method (e.g., air rotary percussion on segmented drill-stem, air diamond kerf drilling on coiled tubing, and cable tool drilling), and each would be automated with state-of-the art systems. When effective automated remote control drilling is demonstrated, a phase II development including a Martian delayed-communication simulator in the remote telemetry system is proposed. This effort, even if it is for the most part unsuccessful, will provide valuable guidance in defining the real control and automation issues.

Hole Stabilization

Our best understanding of what the Martian subsurface might be like suggests that unconsolidated or otherwise unstable zones will make up at least part of the stratigraphic column that a drill to any significant depth will encounter. In addition, the possibility of melting any pore ice or ground ice that may be present could lead to hole instability. Consequently, we believe that a provision for hole stabilization must be provided by any credible, high reliability drilling system. In terrestrial drilling in soils or sedimentary rock, temporary hole stability is usually provided by weighted drilling muds. For reasons discussed above, this approach is not feasible on Mars. An alternative for shallow drilling in surficial materials is overburden drilling in which a concentric casing and drill string is used to place metal casing while drilling. Calculations indicate that normal wall thickness steel casing would not be allowable, but thin-walled aluminum or other low-density, high-strength, thin-wall casing is feasible within our mass constraint. Because of buckling instability, top thrusting of thin-walled casing will be limited, but top sonic emplacement or bottom pull-in or even bottom construction of casing look feasible. There is some experience with such systems, but of course not under Mars conditions. Consequently, we recommend that overburden-type hole stabilization technologies have a high priority for engineering research and demonstration.

Materials Applicability

The final priority recommendation we want to make is for further research and analysis on materials applicable to this problem. Materials issues cut across most of our analyses, but we were unable to give the many questions that arose sufficient time and effort to resolve them. For example, we are not sure how diamond-impregnated bits, optimized for terrestrial conditions, will work under Martian conditions; the cobalt binder that is commonly used in these bits may loose ductility at the low temperatures of Mars. Are common aerospace aluminum and titanium alloys suitable for percussive and shock loads at 200 degrees K? Also, the many polymeric materials that are commonly used in bottom-hole assemblies and logging subs are optimized for much higher temperatures than we will encounter on Mars, and organic materials raise contamination and life-detection issues. Many of these materials issues are generic but some are very drilling-specific. We recommend that more analysis and design research on materials issues be performed to include the range of Martian conditions, with emphasis on low temperatures.

References

1. Clifford, S.M., "The Lithology and Volatile Stratigraphy of the Martian Crust: A Review of Current Speculation," background reference document for deep-drilling and geophysical sounding investigation of the Martian subsurface, Lunar and Planetary Institute, 01/14/2000 Draft.

2. Clarke, J. W. et. al., "The Kola Superdeep Drill Hole by Ye. A. Kozlovskiy – A detailed summary (translation)," USGS Open File Report 86-517, 1986.

3. Oppelt, J., N. Eaton, L. Wohlgemtuh, "Continuous Coring of the KTB: A case History," Geological Society of Lower Saxony, Hannover, Fed. Rep. Of Germany, SCA Conference Paper Number 8912, 1989.

4. Eskin, M., W. C. Maurer, and A. Leviant, "**Former-USSR R&D on Novel Drilling Techniques**," Maurer Engineering, 1995.

5. Maurer, W. C., *Novel Drilling Techniques*, Pergamon Press, London, 1968.

6. Maurer, W. C., *Advanced Drilling Techniques*, Petroleum Publishing Co., Tulsa, OK, 1980.

7. Leising, L. J., E. C. Onyia, S. C. Townsend, P. R. Paslay, and D. A. Stein,   "Extending the Reach of Coiled Tubing Drilling (Thrusters, Equalizers, and Tractors)," SPE 37656 Presented at the SPE/AIDC Drilling Conference, Amsterdam, the Netherlands, 4-6 March, 1997.

8. Riddle, C. H. and P. K. Hardcastle, "Drilling and sampling of Permafrost for Site Investigation," SPE #22139, International Arctic Technology Conference, anchorage Alaska, May 29-31, 1991.

9. Rabia, H. "Technical Note - Specific Energy as a Criterion for Drill Performance Prediction," Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., Vol. 19, pp 39-42, 1982.

10. Teale, R., "The Concept of Specific Energy of Rock Drilling," Int. J. Rock Mech. Min. Sci., Vol. 2, pp 57-73, 1965.

11. Kolle, J., M. Marvin, and M. Celich, "**Coiled Tubing Drilling with Supercritical Carbon Dioxide - Phase 1 SBIR, Final Report**," USDOE SBIR Report, 1999.

12. Cavagnaro, P., R. Simon, and G. Cooper, "**A Successful Borehole Drilled by Cryogenic Drilling in An Arid, Unconsolidated Soil With Boulders**," proceedings of ASME Energy-Sources Technology Conference and Exposition, Houston, TX, Jan. 28-30, 1997.

13. Kutasov, I. M., and R. M. Caruthers, "Hole Enlargement Control During Arctic Drilling," SPE 17442, SPE California Regional Meeting, Long Beach, California, March 23-25, 1988.

14. Abyzbayev, B. I. et al., "**Electro drill provides alternative drilling system**," Oil & Gas Journal, Feb. 9, 1998.

15. Chugh, C. P., Manual *of Drilling Technology*, Rotterdam: A.A. Balkema, 1987.

16. Moore, P. L. et al., "*Drilling Practices Manual*," Petroleum Publishing Co., Tulsa, OK, 1974.

17. Bourgoyne, A. T., K. K. Millheim, M. E. Chenevert, and F. S. Young, *Applied Drilling Engineering*, Society of Petroleum Engineers, Richardson,TX, 1991.

18. Heinz, W. F., *Diamond Drilling Handbook - First Edition,* South African Drilling Association, Johannesburg, Republic of South Africa, 1985.

19. Australian Drilling Industry Training Committee Limited, *Drilling: The Manual of Methods, Applications, and Management*, CRC Press LLC, Lewis Publishers, New York, 1997.

20. Rowley, D. S. and F. C. Appl, "Analysis of Surface Set Diamond Bit Performance," SPE No. 2242, presented at the 43rd Annual Fall Meeting of SPE, Houston, TX, Sept. 29-Oct. 2, 1968.

21. Memarzadeh F.D., and S. Miska, "Numerical Simulation of Diamond-Bit Drilling With Air," SPE No. 12908, presented at the SPE Rocky Mountain Regional Meeting, Casper, WY, May 21-23, 1984.
22. Kramer, S. R., W. J. McDonald, and J. C. Thomson, ***An Introduction to Trenchless Technology***, Van Nostrand Reinhold, New York, NY, 1992.
23. Williams, R. E. et al., "**Advancements in thermal spallation drilling technology**," Los Alamos National Laboratory Report No.   LA-11391-MS, 1988.
24. Wilkinson, M. A., Computational modeling of the gas-phase transport phenomena and experimental investigation of surface temperatures during flame-jet thermal spallation drilling," Doctoral Thesis, Chemical Engineering Department, MIT, Cambridge, MA, 1989.
25. Kolle, J. J., (1997), "A comparison of water jet, abrasive jet and rotary diamond drilling in hard rock," ASME ETCE-98 Drilling Technology Symposium, February 2-4, Houston, TX, (draft ms) pp 8.
26. Foust, A., L. A. Wenzel, C. W. Clump, L. Maus, L. B. Andersen, ***Principals of Unit Operations***, John Wiley & Sons, New York, 1960.
27. Gumenskii, B. M. and N. S. Komarov, ***Soil Drilling by Vibration***, Consultants Bureau Enterprises, Inc., New York, 1961.
28. Bowser-Morner, Inc., "Sonic Technology Description," http://www.bowser-morner.com/sonicdrl.html.
29. JPL's NDEAA Ultrasonic Drilling Homepage http://ndeaa.jpl.nasa.gov/nasa-nde/usdc/usdc.htm
30. Maurer Engineering Inc. Report, ***Underbalanced Drilling and Completion Manual - DEA-101, Phase 1***, Maurer Engineering, 1996.
31. Newman, K. R. and L. R. Stone, "Electric Drilling Motor for Coiled Tubing Drilling – Phase 1, Final Report," Gas Research Institute, CN.   5095-210-3342, 1995.
32. Turner, D. R., T. W. R. Harris, M. Slater, M. A. Yuratich, and P. F. Head, "**Electric Coiled Tubing Drilling: A Smarter CT Drilling System**," SPE 52791, SPE/IADC Drilling Conference, Amsterdam, Holland, 9-11 March, 1999.
33. Russell F. G. et al, Engineering Data Book, Revised 10th Edition, Gas Processors Association, Tulsa Oklahoma, 1987.
34. Bejan, A., ***Convection Heat Transfer***, John Wiley & Sons, New York, 1984.
35. Rabia, H., "A Unified Prediction Model for Percussive and Rotary Drilling," Mining Science and Technology, Vol. 2, p. 207-216, 1985.
36. Clark, G. B., ***Principles of Rock Fragmentation***, John Wiley and Sons, New York, 1987.
37. Finger, J., "Investigation of Percussion Drills for Geothermal Applications," Journal of Petroleum Technology, December 1984.
38. Glocka, D. A., "Use of Single-Cutter Data in the Analysis of PDC Bit Designs: Part 1 – Development of a PDC Cutting Force Model," (SPE 15619) Journal Petroleum Technology, August 1989.
39. Glocka, D. A., "Use of Single-Cutter Data in the Analysis of PDC Bit Designs: Part 2 – Development and Use or the PDCWEAR Computer Code," (SPE 19309) Journal Petroleum Technology, August 1989.
40. Hanold, R. J., et al., "**Rapid Excavation by Rock Melting Drill** – LASL Subterrene Program," LA-5979-SR, Los Alamos National Laboratory Report, 1977.

41. Baumeister, T. *Standard Handbook for Mechanical Engineers, 7th Edition*, McGraw-Hill, Inc., New York.
42. Shigley, J. E., *Mechanical Engineering Design, Third Edition*, McGraw-Hill, Inc., New York, 1977.
43. Globe Motors, Military Product Catalog-m-200, Globe Motors, Dayton, OH.
44. Tain, S. and M. A. Adewumi, "Development of Hydrodynamic-Model-Based Air-Drilling Design Procedures," (SPE 23426) SPE Drilling Engineering, p 241-246, December 1992.
45. Truitt, R. W., *Fundamentals of Aerodynamic Heating*, The Ronald Press Company, New York, 1960
46. Din, F., *Thermodynamic Functions of Gases, Volume 1, Ammonia, Carbon Dioxide and Carbon Monoxide*, Butterworths Scientific Publictions, London, UK, 1956.
47. Van Wylen, G., R. Sonntag, and C. Borgnakke, *Fundamentals of Classical Thermodynamics – 4th Edition*, John Wiley & Sons, New York, 1994.
48. Reynolds, W. C. and H. C Perkins, Engineering Thermodynamics, McGraw-Hill Book Company, New York, 1977.
49. Rohsenow, W. M, J. P. Hartnett, and E. N.Ganic, *Handbook of Heat Transfer Fundamentals* - 2nd *Edition*, McGraw-Hill Book Company, New York, 1985.
50. Maurer, W. C. and J. P. Vozniak, "Progress in Horizontal Wells and Slim-hole Technologies Applications," Presented at the SPE/CIM 4th Annual One-day Conference on Horizontal Wells, Calgary, Alberta, Canada, November 22, 1994.
51. Leising, L. J. and K. R. Newman, "Coiled Tubing Drilling," SPE 24594, SPE Drilling and Completion, December 1993.
52. Maurer, W. C. and W. C. Herben, "**Deep Earth Sampling System** – Phase 1, Final Report," National Science Foundation, ISI –8960064, 1990.
53. Budynas, R. G., Advanced *Strength and Applied Stress Analysis*, McGraw-Hill Book Company, New York, 1977.
54. Quality Tubing Inc., "**QTI Tubing Capacity Chart,**" web page http://www.qualitytubing.com/, 1998.
55. Gelfgat, M. Y. and V. S. Basovich, "Aluminum Tubular in Deep Water Drilling Application," **preprint**.
56. Warren, T. M., L. A. Sinor, and M. W. Dykstra, "Simultaneous Drilling and Reaming with Fixed Blade Reamers," SPE 30474, presented at the SPE ATCE, Dallas, TX, U.S.A., 22-25 October, 1995.
57. American Petroleum Institute, "Formulas for Calculations for Casing, Tubing, Drill Pipe, and Line Pipe Properties," API Bulletin 5C3, Second Editions, November 1974.
58. Stewart, R. B., D. S. Gill, W. C. M. Lohbeck, and M. N. Baaijens, "An Expandable Slotted Tubing, Fibre-Cement Wellbore Lining System," SPE 36828, presented at the SPE European Petroleum Conference, Milan, Italy, 22-24 October, 1996.
59. Stewart, R. B., D. S. Gill, W. C. M. Lohbeck, and M. N. Baaijens, "An Expandable Slotted Tubing, Fibre-Cement Wellbore Lining System" SPE 36583, presented at the 1996 SPE ATCE, Denver, Colorado, U.S.A., 6-9 October, 1996.
60. Eventure Global Technology, "Expandable-Tubular Technology," Commercial brochure, printed June 1999.
61. Cooper, G., Z. Liu, and M. Yang, "Use of Cryogentic Fluids for Enviromental Well Installations, Drilling Technology, PD-Vol. 56, ASME ESTC, 1994.

62. Blacic, J.D., "Mechanical properties of lunar materials under anhydrous, hard vacuum conditions: Applications of lunar glass structural components," in Lunar Bases and Space Activities of the 21st Century, W.W. Mendell, ed., LPI, Houston, 487-495, 1985.

63. Michalske, T.A. and S. W. Freiman, "A molecular interpretation of stress corrosion in silica" Nature, 511-512, 1982.

64. National Research Council, ***Drilling and Excavation Technologies for the Future***, National Academy Press, Washington, D. C., 1994.

65. Network Analysis, Inc., *SINDA/G Users Guide*, Network Analysis Inc., Tempe, AZ, 1999.

66. Rohsenow, W.M., Hartnett, J.P., Ganic, E.N., ed., *Handbook of Heat Transfer Fundamentals*, McGraw-Hill Book Co., New York, 7-156, 1985.

67. Siegel, R., Howell, J.R., *Thermal Radiation Heat Transfer*, Taylor & Francis Ltd., Philadelphia, PA 263-278, 1992.

68. Anderson, A.F., Jameson, R.J., Johnson, A.L., Stake, R.T., Wright, R. M. "Radiator Design for Space Vehicles," Airesearch Manufactruing Co, 1975.

69. Heywood, J.B., *Internal Combustion Engine Fundamentals*, McGraw-Hill Book Co., New York, 1988.

Appendices and Attachments

Appendix A. Core Drill Thermal Model

A finite difference thermal model of a diamond coring drill was developed to calculate the impact of drilling specific energy, rate of penetration, bit configuration, and cooling requirements on the core produced for biologic and geologic sampling. This study required that samples be held within 10 K of their in situ state while drilling and transport to the surface; thus, a model was required to approximate core temperatures and the cooling needed to meet this requirement. This axi-symmetric SINDA model accounts for conduction, convection, and radiation between the drill, core, and formation [65]. The drill geometry, material properties, specific energy to break the rock, and rate of penetration can be varied to calculate the temperatures and cooling requirements. It is assumed that all of the energy required to break the rock is expended at the cutting surface at the bottom of the bit. A slight gap is assumed between the drill and core, and drill and formation. Convection and radiation are modeled across this gap [66,67]. Cooling is modeled by simply attaching the drill at the desired location to a constant temperature sink. The cooling systems described elsewhere in this report were sized to provide this desired sink temperature.

As the drill moves down through the formation, the nodes which make up the kerf are disconnected from the model (transported out of the hole), and the drill is connected to the appropriate sections of the formation as it progresses downward. Two sets of boundary nodes move with the drill to account for convection and radiation without generating an unmanageably large model. The temperatures of these nodes are changed at each time step based on the drill position and on the drill, core, and formation temperatures to provide the appropriate boundary temperatures for radiation and convection to the adjacent surfaces and fluid. To improve the accuracy of the results, the time step can be varied independently from the penetration rate. Figure A1 shows a schematic of the model.
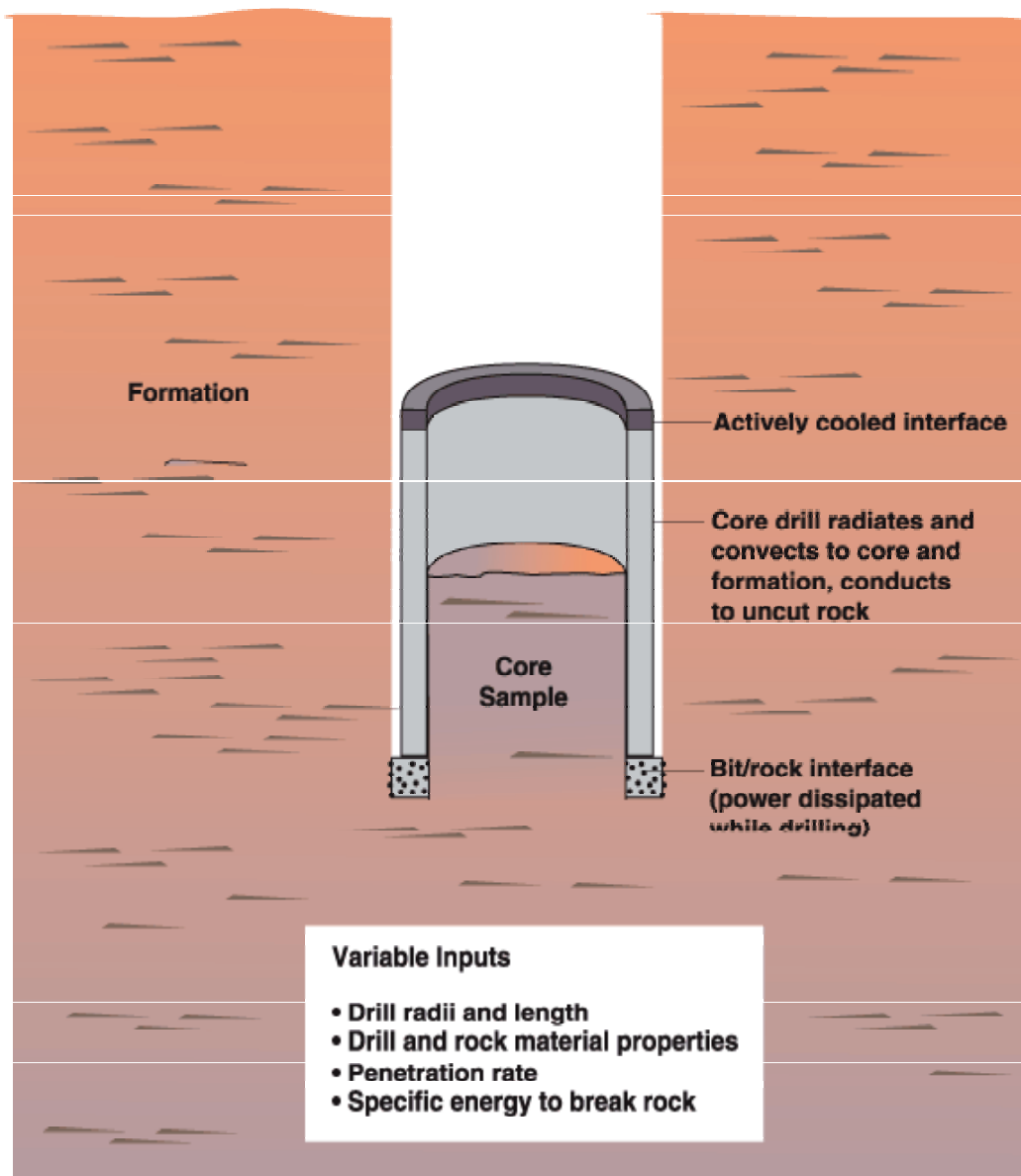
Figure A1. Core drill model

Appendix B. Radiator Model

A potentially significant component of the drilling system is the radiator that may be required to reject most of the system available energy (1 kW hr/Sol). Since this was a large and potentially massive component, a model was developed to estimate the size and weight of the radiator for various mission scenarios (e.g., drill during day/cool during night, or drill-and-cool

at night using batteries), and various cooling systems (e.g., liquid loop, or refrigeration cycle). A schematic of the model is shown in Figure B1. The model uses SINDA to calculate the temperature distribution in a single channel and fin of the radiator, and then uses the heat rejection requirements to calculate a total size and mass [65, 68]. The fluid and radiator material properties and geometry can be varied. The model will iterate until the radiator is sized to achieve the desired exit temperature, given the inlet temperature, mass flow rate, and heat rejection required. The following values were typically used although they can be varied in the model:

Sky sink Temperature:	145 K
Radiator emissivity:	0.8
Solar flux (daylight operation):	589 W/m^2
Solar absorptivity (daylight operation):	0.32
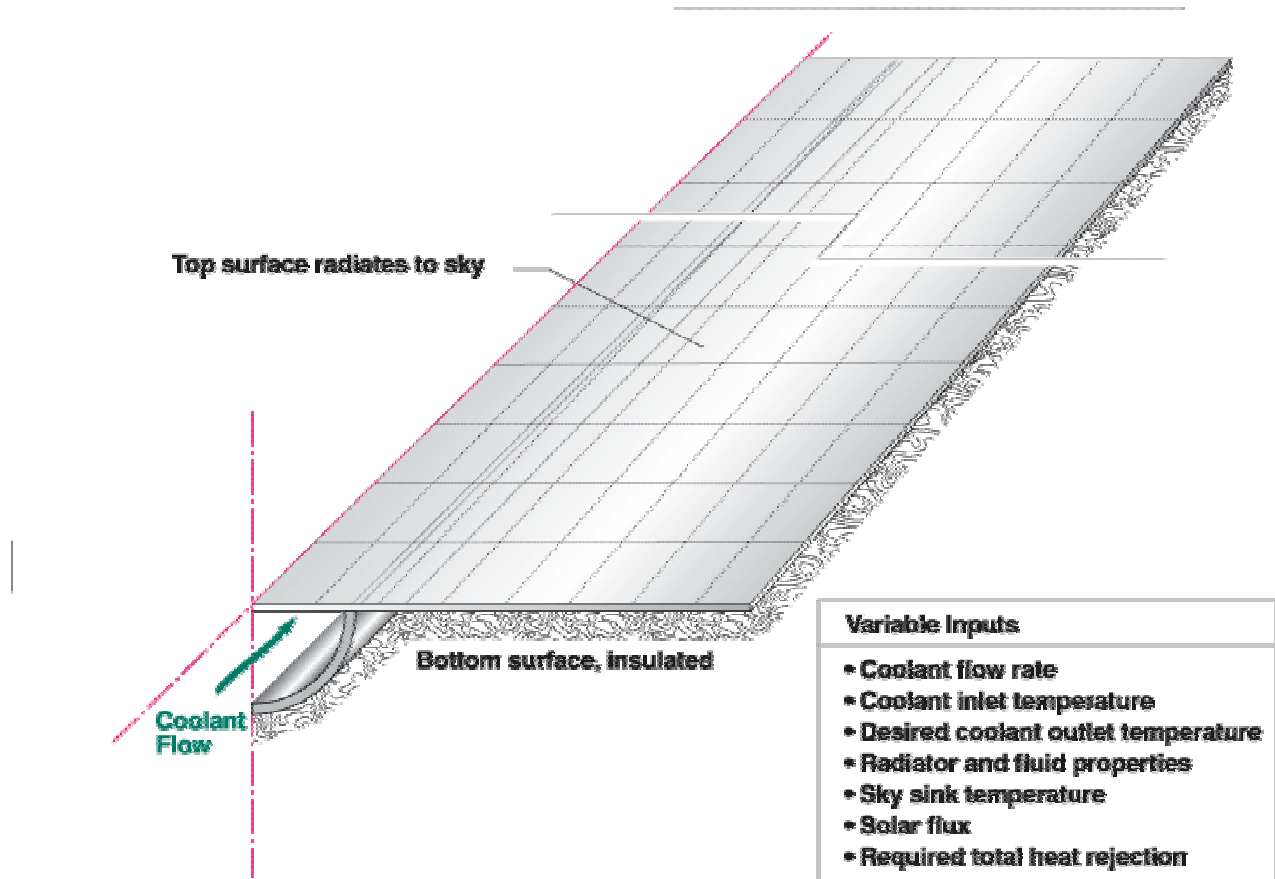
Figure B1. Radiator Model Schematic

Appendix C. Rock Melting Drill Model

In order to assess the impact of a high temperature rock melting drill on the acquisition of samples at near in situ conditions, a finite difference model of a rock melting bit and surrounding formation was developed. The results can be used to estimate the depth required for coring

operations in order to reach rock which is thermally unaffected by the drilling process. Two models were developed. The first is an axi-symmetric model of an existing LANL rock-melting bit. The model includes the many different materials, contact conductances, radiation through gaps and cavities, convective cooling inside of the bit, and the resistivity of the pyrolytic graphite heater. A fixed temperature boundary condition is applied on the exterior of the model, which represents the formation temperature. The second model is a one-dimensional model of the rock formation that is being melted. The model represents a point on the bore hole wall as the bit moves past. From this model, temperature profiles as a function of time and depth into the formation can be estimated. The model includes phase change, and temperature dependent properties. The temperature at the point of contact between the rock formation and the bit is obtained from the bit model described above. Various bit power levels, cooling schemes, and penetration rates can be investigated by iteratively running the two models.

Appendix D. Compressor Mass Model

In order to size compressors for the various subsystems required for this study, several techniques were used. Existing compressor designs were scaled and conceptual design codes were available for use. However, many of the systems being investigated for this study had very small corrected flows, making scaling and the results from available codes inaccurate. A very simple model of a positive displacement compressor was developed to estimate the masses of small compressors [33, 70]. The model includes the thermodynamics of a single piston compressor required to provide the desired mass flow and pressure ratio. The piston and connecting rod loads are calculated, and then used to estimate component masses. The results include a very rough compressor mass estimate and compressor operating characteristics (rotation speed, piston speed, temperature, and power).

Long List of Potential Drilling Techniques for Drilling 200-m Deep Bore on Mars in Support of Subsurface Sampling

	System					Description of Sub-systems				
No.	Name of Drilling Method	Refs.	Rock and Soil Comminution	Drill Conveyance	Drill Cuttings Transport	Well Stabilization	Power Transmission	Bottomhole Power Conversion	PM&C[11] Downhole Telemetry	Downhole Thermal Management
1	**Surface Percussion Drills**		Rotary percussion drills with surface power units that reciprocate and rotate the drill stem to power a down hole bit or core head.							
A	Jack Hammer Drifter	[1, 18]	Mech. Rotary/ Percussion	T&C[4] Drill Steel[4]	Pneumatic	Densified Wall	Mechanical Reciprocation/Rotary/Pneumatic	Percussion Impact Rotary Indexing	DHT[12] not supported	Air Cooling
B	Sonic Drill Mechanical Vibrator	[7, 19]	Mechanical Percussion/ Rotation	T&C Drill Rods	Continuous Core	Densified Wall	Mechanical Reciprocation / Rotation	Percussion Impact Rotary Indexing Kerf Core Head	DHT not supported	Bit to Drill Rod to Rock and Core
C	Ultrasonic/sonic drill/corer	[17]	Mechanical Percussion	T&C Drill Rods	Continuous Core	Densified Wall	Mechanical Reciprocation	Percussion Impact Kerfing Corehead	DHT not supported	Bit to Drill Rod to Rock and Core
2	**Cable Deployed Drills**		Drilling assemblies deployed on a mechanical wireline (sandline) or electric wireline (mechanical, telemetry, and/or electric power)							
A	Percussion Churn **Mud**[1]	[1,18]	Mechanical Percussion	Umbilical **Sandline**[5]	Mud Slurry Bailer	Filter Cake / Densified Wall	Mechanical Reciprocation	Gravity Accelerated Impact w/Cable Wrap Indexing	DHT using Wireline	Bit to Liquid to Formation
B	Percussion Churn **Air**[2]	[1,18]	Mechanical Percussion	Umbilical **Sandline**[5]	Scow Bailer / Bucket Auger	Filter Cake / Densified Wall	Mechanical Reciprocation	Gravity Accelerated Impact w/Cable Wrap Indexing	DHT using Wireline	Bit to Cuttings to Formation
C	Electrodrill	[7]	Mechanical Rotary	Umbilical **Wireline w/power cable**[7]	Mud Slurry Bailer	Filter Cake / Densified Wall	Electric	Rotary Gouge / Electric Motor	DHT using Wireline	Bit to Liquid to Formation
3	**Rotary Drills**		Drilling assemblies deployed on segmented drill stem and rotated from the surface with a rotary table on the rig floor or a top drive power swivel.							
A	Mud Rotary	[1, 2, 3]	Mechanical Rotary	**T&C Drill Pipe**[4]	Hydraulic Slurry	Filter Cake and Hydrostatic Fluid	Mechanical Rotary / Hydraulic	Rotary Gouge (Percussion Impact multi-cone)	Mud Pulse Telemetry	Liquid Cooling
B	Air Rotary	[4, 18]	Mechanical Rotary	T&C Drill Pipe	Pneumatic Slurry	None, **TBD**[6]	Mechanical Rotary / Pneumatic	Rotary Gouge (Percussion Impact multi-cone)	Drill Stem Acoustic Telemetry	Air Cooling
C	Mud Diamond (Kerf) Coring	[5, 18]	Mechanical Rotary	**T&C Drill Rods**[4]	**Continuous Core**[10]/Hydraulic Slurry	Filter Cake and Hydrostatic Fluid	Mechanical Rotary / Hydraulic	Rotary Gouge Core Head	DHT not supported	Liquid Cooling
D	Air Diamond (Kerf) Coring	[4, 5, 18]	Mechanical Rotary	T&C Drill Rods	**Continuous Core**[10]/Pneumatic Slurry	None, TBD	Mechanical Rotary / Pneumatic	Rotary Gouge Core Head	DHT not supported	Air Cooling
4	**Downhole Motor and Rotary Hammer Drills**		Drilling assemblies deployed on coiled tubing and rotated and/or reciprocated using downhole rotary motors and/or hammers. These systems can be deployed on segmented drill stem (and rotated from the surface to eliminate the need for a downhole rotary or indexing motor) but telemetry is more difficult.							
A	Mud Powered Hydraulic **Motor**[3]	[3, 6]	Mechanical Rotary/ Percussion	**Continuous Tubing**[4]	Hydraulic Slurry	Filter Cake and Hydrostatic Fluid	Hydraulic	Rotary Gouge Percussion Impact / Hydraulic Motor/Hammer	Telemetry Cable in Continuous Tubing	Liquid Cooling
B	Air Powered Pneumatic Motor	[4]	Mechanical Rotary/ Percussion	Continuous Tubing	Pneumatic Slurry	Densified Wall	Pneumatic	Rotary Gouge Percussion Impact / Pneumatic Hammer/Motor	Telemetry Cable in Continuous Tubing	Air Cooling
C	Electric Motor with Air Cooling	[7, 8, 9, 10]	Mechanical Rotary	Umbilical **Wireline**[5] w/power cable	Pneumatic Slurry	None, TBD	Electric / Pneumatic	Rotary Gouge (Percussion Impact multi-cone) / Electric Motor	DHT using Wireline	Air Cooling
D	Ultrasonic Drill	[11, 17]	Abrasion and Cavitation	**Continuous Tubing w/Utilities**[7]	Hydraulic Slurry	Filter Cake and Hydrostatic Fluid	Electric / Hydraulic	Electric or Hydraulic Acoustic Horn	Telemetry Cable in Continuous Tubing	Liquid Cooling
5	**Piercing Soil Drills**		Soil piercing and ramming assemblies deployed on segmented push rods design to transmit high compressive impact loads.							
A	Thrust boring	[20]	Local formation compaction	**T&C Push Rods**[4]	Displaced into adjoining soil	Densified Wall	Mechanical Axial Translation	Direct Mechanical Compaction	DHT not supported	Pierce Mandrel to Push Rod to Soil
B	Impact Moling	[20]	Local formation compaction	T&C Push Rods	Displaced into adjoining soil	Densified Wall	Mechanical Axial Translation	Direct Mechanical Compaction	DHT not supported	Pierce Mandrel to Push Rod to Soil
6	**Overburden Drilling Systems**		Drilling systems based on advancing a casing for borehole stabilization in unstable surface formations while or before drilling a smaller diameter hole to penetrate harder formation where these systems will not drill.							
A	Impact Ram Piercing	[20]	Coring, Local Compaction, Erosion	Special Piercing Casing	Plug Core / Compacted in adjoining soil	Casing While Drilling, Densified Wall	Mechanical Axial Translation / Hydraulic	Direct Mechanical Compaction	DHT not supported	Liquid Cooling/Pierce Mandrel to Push Rod to Soil
B	Hollow stem auger	[18]	Mechanical Rotary	Hollow stem auger sections	Auger + Continuous Core	Casing While Drilling	Mechanical Rotary	Auger Screw	DHT not supported	Auger Drill Stem to Formation
C	Eccentric Reamer ODEX8	[18]	Mech. Rotary/ Percussion	Drill Pipe + Special **ODEX**[TM] **Casing**[8]	Pneumatic Slurry	Casing While Drilling	Mechanical Reciprocation/Rotary/Pneumatic	Rotary Gouge Percussion Impact	DHT using **WLDHC**[13]	Air Cooling
D	Dual Rotary Drilling	[18]	Mechanical Rotary	Drill Pipe + Special **LH Thrd.**[9] Casing	Pneumatic Slurry	Casing While Drilling	Mechanical Rotary/Pneumatic	RH Rotary Gouge Bit / LH Rotary Gouge Casing Shoe	DHT using WLDHC	Air Cooling
E	Wireline Retractable Drill/Casing Advancer	[18]	Mechanical Rotary	Casing Shoe w/Wireline Bit Replacement	Pneumatic Slurry	Casing While Drilling	Mechanical Reciprocation/Rotary/Electric/Pneumatic	Rotary Gouge Percussion Impact	DHT using Wireline	Air Cooling
7	**Subterranean Moles**		Systems based on a self propelled drilling machine that closes the hole behind itself or fills a large fraction of the hole behind itself leaving a small diameter hole on an umbilical connection to the surface which serves a conduit for power, cooling fluid circulation and cuttings disposal.							
A	Guided Impact Mole	[20]	Local formation compaction	Self propelled mole / umbilical	Displaced into adjoining soil	Densified Wall	Hydraulic or Pneumatic	Direct Mechanical Compaction	DHT using cable in Umbilical	Pierce Mandrel to Soil and Power Fluid
B	Percussion Mole	[JPL+RDS]	Mech. Rotary/ Percussion	Self propelled mole / umbilical	Repack cuttings behind the mole	Densified Wall and Re-packed Hole	Electric or Hydraulic	Percussion Impact Rotary Indexing / Electric Motor	DHT using cable in Umbilical	Mole to Cuttings and Rock (and Umbilical?)
8	**Jet and Cavitation Drills**		Drills that produce holes with a high velocity fluid jet impacting the rock to cause brittle failure or eroding the rock. These systems are assumed to be deployed on coiled tubing and rely on downhole motors or angled jets if rotation of the jet(s) is required.							
A	High Pressure Continuous or Pulsed	[12]	Hydraulic Impact/Erosion	Continuous Tubing w/Utilities	Hydraulic Slurry	Filter Cake or Densified Wall	Hydraulic	Continuous or Pulsed Hydraulic Jet	Telemetry Cable in Continuous Tubing	Liquid Cooling
B	Cavitating Jets	[7, 12]	Hydraulic Impact/Cavitation	Continuous Tubing w/Utilities	Hydraulic Slurry	Filter Cake or Densified Wall	Hydraulic	Implosion of Vapor Cavities in a Jet	Telemetry Cable in Continuous Tubing	Liquid Cooling
C	Electric Spark Drill	[12]	Hydraulic Impact/Cavitation	Continuous Tubing w/Utilities	Hydraulic Slurry	Filter Cake or Densified Wall	Hydraulic	Electric Spark Shock Wave Generator	Telemetry Cable in Continuous Tubing	Liquid Cooling
D	Abrasive Jets	[7, 12]	Particle Impact/Erosion	Continuous Tubing w/Utilities	Pneumatic Slurry	None, TBD	Pneumatic	Acceleration of Particles in a Pneumatic Expansion Jet	Telemetry Cable in Continuous Tubing	Air Cooling
E	Supercritical CO2 Jet Rotary Drill	[13]	Chemical/Hydraulic Erosion/Mech.	Continuous Tubing w/Utilities	Pneumatic Slurry	None, TBD	Pneumatic / Chemical / Mech. Rotary	Rotary Gouge/ High Velocity Jets / Pneumatic Motor	Telemetry Cable in Continuous Tubing	CO2 Circulation
9	**Thermal Spallation Drills**		Drilling using rapid downhole heating of rock to induce thermal spallation (rapid temperature change to produce near surface stress failure of the exposed rock. These systems are assumed to be deployed on coiled tubing and rely on downhole motors if rotation of the jet(s) is required.							
A	Flame Jet Spallation	[12, 14]	Thermal Stress Spallation	Continuous Tubing w/Utilities	Pneumatic Slurry	Partial glass lining	Chemical / Pneumatic	Chemical Combustion / Thermal Spallation	Telemetry Cable in Continuous Tubing	Air Circulation and Expansion
B	Rocket Exhaust	[11, 12]	Thermal Stress Spallation	Continuous Tubing w/Utilities	Pneumatic Slurry	Partial glass lining	Chemical / Pneumatic	Chemical Combustion / Thermal Spallation	Telemetry Cable in Continuous Tubing	Water circulation and steam formation
C	Microwave Spallation	[7, 11]	Thermal Stress Spallation	Continuous Tubing w/Utilities	Pneumatic Slurry	Partial glass lining	Electric / Pneumatic	Microwave Generator / Thermal Spallation	Telemetry Cable in Continuous Tubing	Air Circulation and Expansion
D	Thermal Shock (Reverse Spallation)	[7, 21]	Reverse Thermal Stress Spallation	Continuous Tubing w/Utilities	Pneumatic Slurry	Freezing moisture in formations	Cryogenic gas/liquid flow	Cryogenic Expansion / Thermal Spallation	Telemetry Cable in Continuous Tubing	Cryogenic Fluid Expansion
10	**Rock Melting Drills**		These are a family of systems based on partial or complete fusion of rock to produce a densified cast bore lining and excess melt removed by extrusion & solidification of small particles.							
A	Rock Melting Drill	[7, 11, 12, 15]	Thermal Fusion	Continuous Tubing w/Utilities	Extruded Melt in Pneumatic Slurry	Densified and Annealed Glass	Electric / Pneumatic	Electric Heater / Fusion	Telemetry Cable in Continuous Tubing	Air Circulation and Expansion
B	Microwave Melting	[7]	Thermal Fusion	Continuous Tubing w/Utilities	Extruded Melt in Pneumatic Slurry	Densified and Annealed Glass	Electric / Pneumatic	Microwave Generator / Fusion	Telemetry Cable in Continuous Tubing	Air Circulation and Expansion
C	Electric Arc and Plasma	[7, 11, 12]	Thermal Fusion	Continuous Tubing w/Utilities	Extruded Melt in Pneumatic Slurry	Densified and Annealed Glass	Electric / Pneumatic	Spark or Arc Plasma Heater / Fusion	Telemetry Cable in Continuous Tubing	Water Circulation
D	Laser Drill	[7, 11, 12]	Thermal Fusion /Spallation	Continuous Tubing w/Utilities	Extruded Melt in Pneumatic Slurry	Melted and fused bore wall	Electric / Pneumatic	Optical Absorption Heating / Fusion / Stress Wave Generation	Telemetry Cable in Continuous Tubing	Air Circulation and Expansion
No.	Name of Drilling Method	Refs.	Rock and Soil Comminution	Drill Conveyance	Drill Cuttings Transport	Well Stabilization	Power Transmission	Bottomhole Power Conversion	PM&C[11] Downhole Telemetry	Downhole Thermal Management

Footnotes

1. Mud implies **liquid** drilling fluids including water, natural mud, bentonite base mud, or polymer-based mud.

2. Air implies Martian atmosphere primarily CO_2 at a uncompressed pressure of 800 Pa + ~200 Pa.

3. Motor and/or Hammer implies downhole transmitted power conversion to **rotary and/or reciprocating** mechanical

4. **T&C** = threaded and coupled segmented drill stem. **Drill steels** are hollow, thick-walled steel rods designed to convey high reciprocating compressive loads from the surface to the bit. **Drill pipe** has externally/internally upset tool-joint-connection design for high tensile and torsion loads and a pipe diameter of 0.2 to 0.7 times the bore diameter. **Drill rods** have flush-joint external connections and a pipe diameter > 0.7 times the bore diameter that is designed for high speed rotation obtaining laterally significant support from contact with the bore wall. **Push rods** are 3 to 5-ft (1 to 1.7-m) long, threaded and coupled solid rods or heavy wall steel tubes. **Continuous Tubing** is coiled or reeled tubing that is inserted and retracted from the bore much like a wireline and can be inserted and retracted with out cessation of circulation, power transmission, or telemetry. **Umbilical** are flexible wirelines or tethers with water/power cable, and hydraulic/pneumatic hoses.

5. A **sandline** is a structural steel wire cable with no copper or fiber optic telemetry. A **wireline** is a telemetry (wire or fiber optic) cable wrapped inside a structural steel armor cable so that the entire cable is self-supporting in a deep hole.

6. **TBD** = to be determined. Commercial system or prototype technology is unknown or does not exist or effect of drilling method on hole stability is not obvious or known.

7. **w/Utilities** = with utilities installed inside of the tube or cable that may include telemetry or fiber optic cables, and electric power cable, and/or hydraulic or pneumatic tubing.

8. **ODEX**[TM] = overburden eccentric drilling. Commercial advanced casing-while-drilling system for shallow unconsolidated and unstable formations [1]. The system uses an under-reaming bit that can be run and withdrawn through the casing. The bottom of the casing is tipped with hard facing and the casing is advanced with percussion.

9. **LH Thread.** = Left hand threaded casing. Casing is advanced with a dual rotary table that **Right Hand** rotates a conventional drilling system with an eccentric, extractable, under-reaming bit inside a **Left Hand** rotating casing string with a rotary drilling shoe on bottom.

10. **Continuous Core** with thin wall T&C drill stem, drill rods or hollow stem augers supports wireline core retrieval.

11. **PM&C** = process monitoring and control – Long list addresses downhole telemetry presently supported or conceptually supported by the system concept proposed

12. **DHT** = downhole telemetry support through or in drill stem. Telemetry for some systems is not supported in commercial or prototype systems that we are aware of.

13. **WLDHC** = wireline downhole connection. This is a wireline that is run through a top drive rotary swivel or surface tubing thruster and through the inside of a T&C drill stem or push rod after the bit is set on the bottom of the hole. It is then plugged into the bottom-hole assembly using wet-connect technology that would be a dry connection in air drilling or thrust boring.

Reference List

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3. Bourgoyne, A. T., K. K. Millheim, M. E. Chenevert, and F. S. Young, *Applied Drilling Engineering*, Society of Petroleum Engineers, Richardson,TX, 1991.
4. Maurer Engineering Inc. Report, "*Underbalanced Drilling and Completion Manual - DEA-101*, Phase 1," Maurer Engineering, 1996.
5. Heinz, W. F., *Diamond Drilling Handbook - First Edition*, South African Drilling Association, Johannesburg, Republic of South Africa, 1985.
6. Maurer, W. C. and W. C. Herben, "Deep Earth Sampling System – Phase 1, Final Report," National Science Foundation, ISI –8960064, 1990.
7. Eskin, M., W. C. Maurer, and A. Leviant, *Former-USSR R&D on Novel Drilling Techniques*, Maurer Engineering, 1995.
8. Abyzbayev, B. I. et al., "Electro drill provides alternative drilling system," Oil & Gas Journal, Feb. 9, 1998.
9. Newman, K. R. and L. R. Stone, "Electric Drilling Motor for Coiled Tubing Drilling – Phase 1, Final Report," Gas Research Institute, CN. 5095-210-3342, 1995.
10. Turner, D. R., T. W. R. Harris, M. Slater, M. A. Yuratich, and P. F. Head, "Electric Coiled Tubing Drilling: A Smarter CT Drilling System," SPE 52791, SPE/IADC Drilling Conference, Amsterdam, Holland, 9-11 March, 1999.
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15. Hanold, R. J., et al., "Rapid Excavation by Rock Melting Drill – LASL Subterrene Program," LA-5979-SR, Los Alamos National Laboratory Report, 1977.
16. National Research Council, *Drilling and Excavation Technologies for the Future*, National Academy Press, Washington, D. C., 1994.
17. JPL's NDEAA Ultrasonic Drilling Homepage http://ndeaa.jpl.nasa.gov/nasa-nde/usdc/usdc.htm

Short List of Potential Drilling Techniques for Drilling 200-m Deep Bore on Mars in Support of Subsurface Sampling

No.	System					Description of Sub-systems				
SL	Name of Drilling Method	Refs.	Rock and Soil Comminution	Drill Conveyance	Drill Cuttings Transport	Well Stabilization	Power Transmission	Bottomhole Power Conversion	PM&C[11] Downhole Telemetry	Downhole Thermal Management
Mechanical	**Overburden Drilling Systems**		Drilling systems based on advancing a casing for borehole stabilization in unstable surface formations while or before drilling a smaller diameter hole to penetrate harder formation where these systems will not drill.							
1	Hollow stem auger	[18]	Mechanical Rotary	Hollow stem auger sections	Auger + **Continuous Core**[10]	Casing While Coring	Mechanical Rotary	Auger Screw	DHT not supported	Auger Drill Stem to Formation
2	**Eccentric Reamer**									
A	Conventional **ODEX**[8]	[18]	Mech. Rotary/ Percussion	Drill Pipe + Special ODEX™ Casing[8]	Pneumatic Slurry	Casing While Drilling	Mechanical Reciprocation/Rotary/Pneumatic	Rotary Gouge Percussion Impact	DHT using **WLDHC**[13]	Air Cooling
B	Air Rotary	[4, 18]	Mechanical Rotary	T&C Drill Pipe + Special ODEX™ Casing[8]	Pneumatic Slurry	Casing While Drilling	Mechanical Rotary / Pneumatic	Rotary Gouge (Percussion Impact multi-cone)	Drill Stem Acoustic Telemetry	Air Cooling
C	Air Powered Pneumatic Motor	[4]	Mechanical Rotary/ Percussion	Continuous Tubing+Special ODEX™Casing[8]	Pneumatic Slurry	Casing While Drilling	Mechanical Reciprocation/Rotary/Pneumatic	Rotary Gouge Percussion Impact / Pneumatic Hammer/Motor	Telemetry Cable in Continuous Tubing	Air Cooling
3	**Dual Rotary Drilling**									
A	Conventional Mechanical Rotary	[18]	Mechanical Rotary	Drill Pipe + Special LH Thrd.[9] Casing	Pneumatic Slurry	Casing While Drilling	Mechanical Rotary/Pneumatic	RH Rotary Gouge Bit / LH Rotary Gouge Casing Shoe	DHT using WLDHC	Air Cooling
B	Sonic Drill Mechanical Vibrator	[7, 19]	Mechanical Percussion/ Rotation	T&C Drill Rods + Spec. LH Thrd.[9] Casing	Continuous Core	Casing While Drilling	Mechanical Reciprocation / Rotation	Percussion Impact Rotary Indexing Kerf Core Head	DHT not supported	Bit to Drill Rod to Rock and Core
C	Ultrasonic/sonic drill/corer	[17]	Mechanical Percussion	T&C Drill Rods + Spec. LH Thrd.[9] Casing	Continuous Core	Casing While Drilling	Mechanical Reciprocation	Percussion Impact Kerfing Corehead	DHT not supported	Bit to Drill Rod to Rock and Core
D	Air Diamond (Kerf) Coring	[4, 5, 18]	Mechanical Rotary	T&C Drill Rods + Spec. LH Thrd.[9] Casing	**Continuous Core**[10]/Pneumatic Slurry	Casing While Coring	Mechanical Rotary / Pneumatic	Rotary Gouge Core Head	DHT not supported	Air Cooling
4	**Wireline Retractable Drill/Casing Advancer**									
A	Conventional Mechanical Wireline Retractable	[18]	Mechanical Rotary	Casing Shoe w/Wireline Bit Replacement	Pneumatic Slurry	Casing While Drilling	Mechanical Reciprocation/Rotary/Electric/Pneumatic	Rotary Gouge Percussion Impact	DHT using Wireline	Air Cooling
B	Electric Motor with Air Cooling	[7, 8, 9, 10]	Mechanical Rotary	Umbilical **Wireline**[5] w/power cable	Pneumatic Slurry	Casing While Drilling	Electric / Pneumatic	Rotary Gouge (Percussion Impact multi-cone) / Electric Motor	DHT using Wireline	Air Cooling
C	Percussion Churn **Air**[2]	[1,18]	Mechanical Percussion	**Sandline**[5] drill under advancing casing	Scow Bailer / Bucket Auger	Casing While Drilling	Mechanical Reciprocation	Gravity Accelerated Impact w/Cable Wrap Indexing	DHT using Wireline	Bit to Cuttings to Formation
5	**Subterranean Moles**		Systems based on a self propelled drilling machine that closes the hole behind itself or fills a large fraction of the hole behind itself leaving a small diameter hole for an umbilical connection to the surface which serves a conduit for power, cooling fluid circulation and cuttings disposal.							
A	Percussion Mole	[JPL+RDS]	Mech. Rotary/ Percussion	Self propelled mole / umbilical	Repack cuttings behind the mole	Densified Wall and Re-packed Hole	Hydraulic or Electric	Percussion Impact Rotary Indexing / Electric Motor	DHT using cable in Umbilical	Mole to Cuttings and Rock (and Umbilical?)
Thermal										
6	**Rock Melting Drills**		These are a family of systems based on partial or complete fusion of rock to produce a densified cast bore lining and excess melt removed by extrusion & solidification of small particles.							
A	Conduction Melting	[7, 11, 12, 15]	Thermal Fusion	Continuous Tubing w/Utilities	Extruded Melt in Pneumatic Slurry	Densified and Annealed Glass	Electric / Pneumatic	Electric Heater / Fusion	Telemetry Cable in Continuous Tubing	Air Circulation and Expansion
B	EM Melting (LASER and Microwave)	[7, 11, 12]	Thermal Fusion	Continuous Tubing w/Utilities	Extruded Melt in Pneumatic Slurry	Densified and Annealed Glass	Electric / Pneumatic	EM Radiation Generator / Fusion	Telemetry Cable in Continuous Tubing	Air Circulation and Expansion
C	Electric Arc and Plasma Melting	[7, 11, 12]	Thermal Fusion	Continuous Tubing w/Utilities	Extruded Melt in Pneumatic Slurry	Densified and Annealed Glass	Electric / Pneumatic	Spark or Arc Plasma Heater / Fusion	Telemetry Cable in Continuous Tubing	Water Circulation
SL	Name of Drilling Method	Refs.	Rock and Soil Comminution	Drill Conveyance	Drill Cuttings Transport	Well Stabilization	Power Transmission	Bottomhole Power Conversion	PM&C[11] Downhole Telemetry	Downhole Thermal Management

Footnotes

1. Mud implies **liquid** drilling fluids including water, natural mud, bentonite base mud, or polymer-based mud.
2. Air implies Martian atmosphere primarily CO_2 at a uncompressed pressure of 800 Pa + ~200 Pa.
3. Motor and/or Hammer implies downhole transmitted power conversion to **rotary and/or reciprocating** mechanical
4. **T&C** = threaded and coupled segmented drill stem. **Drill steels** are hollow, thick-walled steel rods designed to convey high reciprocating compressive loads from the surface to the bit. **Drill pipe** has externally/internally upset tool-joint-connection design for high tensile and torsion loads and a pipe diameter of 0.2 to 0.7 times the bore diameter. **Drill rods** have flush-joint external connections and a pipe diameter > 0.7 times the bore diameter that is designed for high speed rotation obtaining laterally significant support from contact with the bore wall. **Push rods** are 3 to 5-ft (1 to 1.7-m) long, threaded and coupled solid rods or heavy wall steel tubes. **Continuous Tubing** is coiled or reeled tubing that is inserted and retracted from the bore much like a wireline and can be inserted and retracted with out cessation of circulation, power transmission, or telemetry. **Umbilical** are flexible wirelines or tethers with telemetry and power cable, and hydraulic/pneumatic hoses.
5. A **sandline** is a structural steel wire cable with no copper or fiber optic telemetry. A **wireline** is a telemetry (wire or fiber optic) cable wrapped inside a structural steel armor cable so that the entire cable is self-supporting in a deep hole.
6. **TBD** = to be determined. Commercial system or prototype technology is unknown or does not exist or effect of drilling method on hole stability is not obvious or known.
7. **w/Utilities** = with utilities installed inside of the tube or cable that may include telemetry or fiber optic cables, and electric power cable, and/or hydraulic or pneumatic tubing.
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Drill Hole Maximum Depth (m)	200			Density of Casing {Aluminum} (kg/m^3)			2796				10 kg/(kW*hr)
BHA Lenth (m)	2			Density of BHA {Titanium} (kg/m^3)			4844				

Maximum Drilling Diameter (mm)	25.0	26.0	27.0	28.0	29.0	30.0	31.0	32.0	33.0	34.0	35.0
OBD System											
Reamed hole diameter (mm)	25.0	26.0	27.0	28.0	29.0	30.0	31.0	32.0	33.0	34.0	35.0
OBD Casing Clearance (mm)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Casing Outside Diameter (mm)	23.0	24.0	25.0	26.0	27.0	28.0	29.0	30.0	31.0	32.0	33.0
Diameter to Thickness(ratio)	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0
Casing Inside Diameter (mm)	20.9	21.8	22.7	23.6	24.5	25.5	26.4	27.3	28.2	29.1	30.0
Coupling Upset on ID (mm)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Minimum Casing ID (mm)	18.9	19.8	20.7	21.6	22.5	23.5	24.4	25.3	26.2	27.1	28.0
Primary Drilling System											
Maximum Hole Diameter (mm)	17.9	18.8	19.7	20.6	21.5	22.5	23.4	24.3	25.2	26.1	27.0
Core diameter (mm)	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Diameter Ratio (DS OD to Hole)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Drill Stem Outside Diameter (mm	12.5	13.2	13.8	14.4	15.1	15.7	16.4	17.0	17.6	18.3	18.9
Diameter to Thickness (ratio)	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Drill Stem Inside Diameter (mm)	10.5	11.1	11.6	12.1	12.7	13.2	13.7	14.3	14.8	15.3	15.9
Coupling Upset on ID (mm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Minimum Drill Stem ID	10.5	11.1	11.6	12.1	12.7	13.2	13.7	14.3	14.8	15.3	15.9

Mass Calculation											
(kg)											
Overburden Hole Stability System											
OBD Casing	41.9	45.7	49.5	53.6	57.8	62.2	66.7	71.4	76.2	81.2	86.4
OBD MU Assembly + Rotary Driv	1.3	1.3	1.4	1.4	1.5	1.5	1.6	1.7	1.7	1.8	1.8
OBD Sonic Drive	4.2	4.6	5.0	5.4	5.8	6.2	6.7	7.1	7.6	8.1	8.6

Hoist			2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.6	3.8	4.1	4.3
Sub OBD System			**49.5**	**53.8**	**58.4**	**63.1**	**68.0**	**73.0**	**78.3**	**83.7**	**89.4**	**95.2**	**101.1**
Primary Drill System													
Primary Drill Stem			20.3	22.4	24.7	27.0	29.4	31.9	34.6	37.3	40.2	43.1	46.2
BHA			4.8	5.1	5.5	6.0	6.4	6.8	7.3	7.8	8.3	8.8	9.3
Bits	8	0.007	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.4
Reamers	8	0.029	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5
CT Reel			2.0	2.2	2.5	2.7	2.9	3.2	3.5	3.7	4.0	4.3	4.6
CT Injector			2.9	3.3	3.8	4.4	5.0	5.6	6.4	7.1	8.0	8.9	9.8
CT Hydraulic Motor			3.6	4.2	4.8	5.5	6.3	7.1	8.0	9.0	10.0	11.1	12.3
CT Hydraulic System			10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Sub CT Drilling System			**43.9**	**47.6**	**51.7**	**56.0**	**60.5**	**65.3**	**70.3**	**75.6**	**81.2**	**87.1**	**93.2**
Cuttings Transport and Cooling System													
Circulation tubing			4.0	4.4	4.8	5.3	5.7	6.2	6.8	7.3	7.8	8.4	9.0
Pump			1.2	1.4	1.6	1.9	2.1	2.4	2.7	3.0	3.4	3.8	4.2
HE equipment			0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.8	1.9	2.0
Misc Hardware			1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Sub Cooling System			**7.1**	**7.8**	**8.5**	**9.3**	**10.2**	**11.0**	**12.0**	**13.0**	**14.0**	**15.1**	**16.2**
Wireline Support System													
Wireline Bailor and Logging System													
Wirleline			7.1	7.7	8.3	8.9	9.6	10.3	11.0	11.7	12.4	13.2	14.0
Bailor			0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.6	0.6
Logging Tool			0.6	0.7	0.7	0.8	0.9	1.0	1.0	1.1	1.2	1.3	1.4
WL Hudualic System			5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Hoist			0.8	0.8	0.9	1.0	1.0	1.1	1.2	1.3	1.4	1.4	1.5
Miscelaneous Hardware			1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Sub Wireline Support System			**14.8**	**15.5**	**16.3**	**17.1**	**17.9**	**18.8**	**19.7**	**20.6**	**21.5**	**22.5**	**23.5**
Lander Surface Systems													
Carousels (2)			17.2	17.4	17.7	17.9	18.2	18.4	18.7	19.0	19.3	19.5	19.8
Carousel/ballscrew motor			2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.6	3.7
Support mast			3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9

Ball screws(3)	2.9	3.1	3.3	3.5	3.7	3.9	4.2	4.4	4.7	5.0	5.2
Core/Casing Robot	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Bottom support platform	26.6	26.7	26.7	26.8	26.8	26.9	26.9	27.0	27.1	27.1	27.2
Liquid cooling-drill night/radiate night(remove 1 kW hr/6.2hr)											
Radiator	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
Batteries	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Sub Lander Surface Support E	**76.8**	**77.3**	**77.9**	**78.5**	**79.1**	**79.8**	**80.4**	**81.1**	**81.9**	**82.6**	**83.4**
Total Mass	**192.0**	**202.1**	**212.8**	**223.9**	**235.6**	**247.9**	**260.7**	**274.0**	**287.9**	**302.4**	**317.5**